Measuring the gluon distribution in nuclei at an Electron-Ion Collider

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U.S. DEPARTMENT OF ENERGY

Lots of work recently on the physics of e+A collisions

The EIC Science case:
a report on the joint
BNL/INT/JLab program

Gluons and the quark sea at high energies: distributions, polarization, tomography

Institute for Nuclear Theory • University of Washington, USA
September 13 to November 19, 2010

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arXiv:1108.1713

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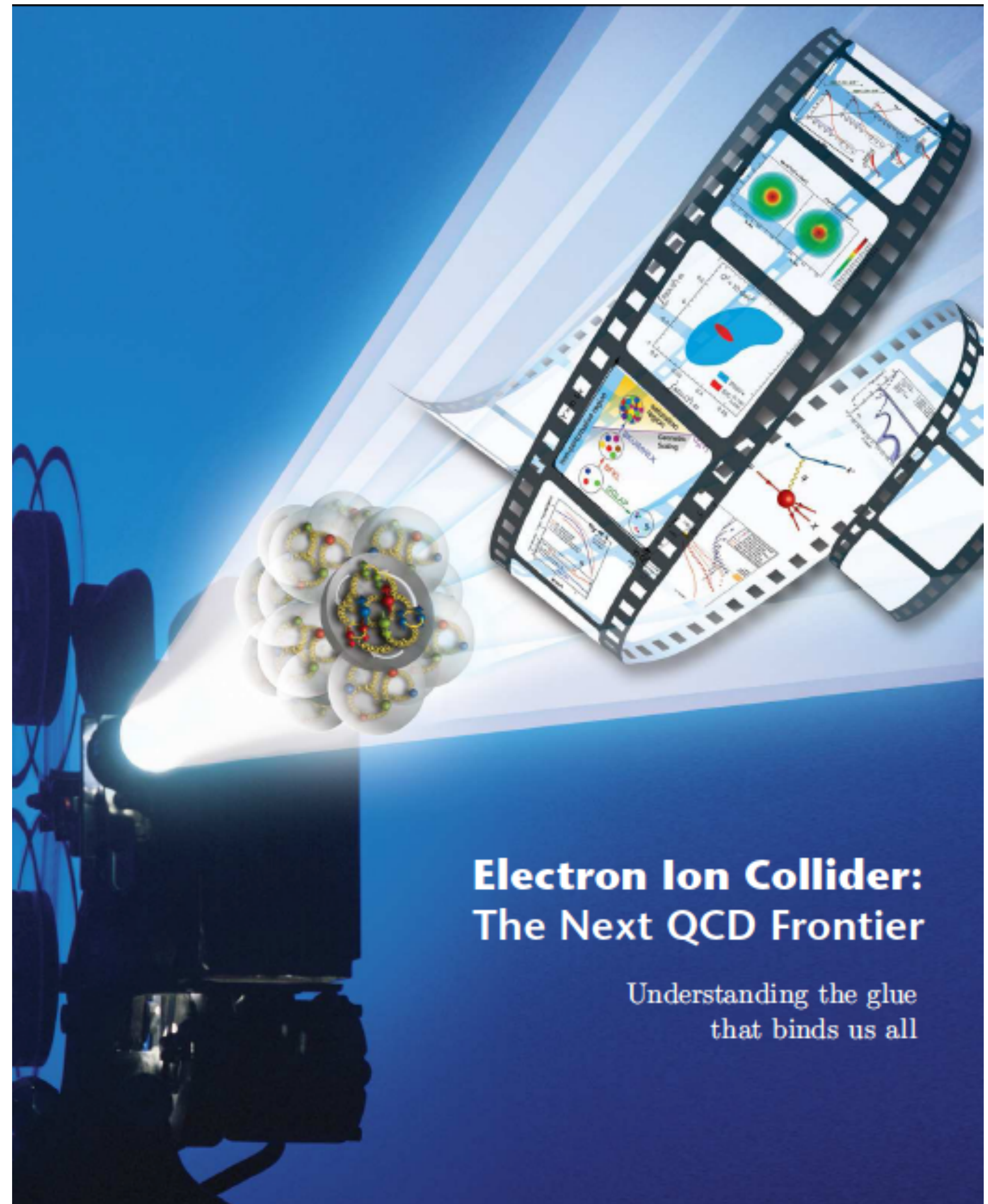
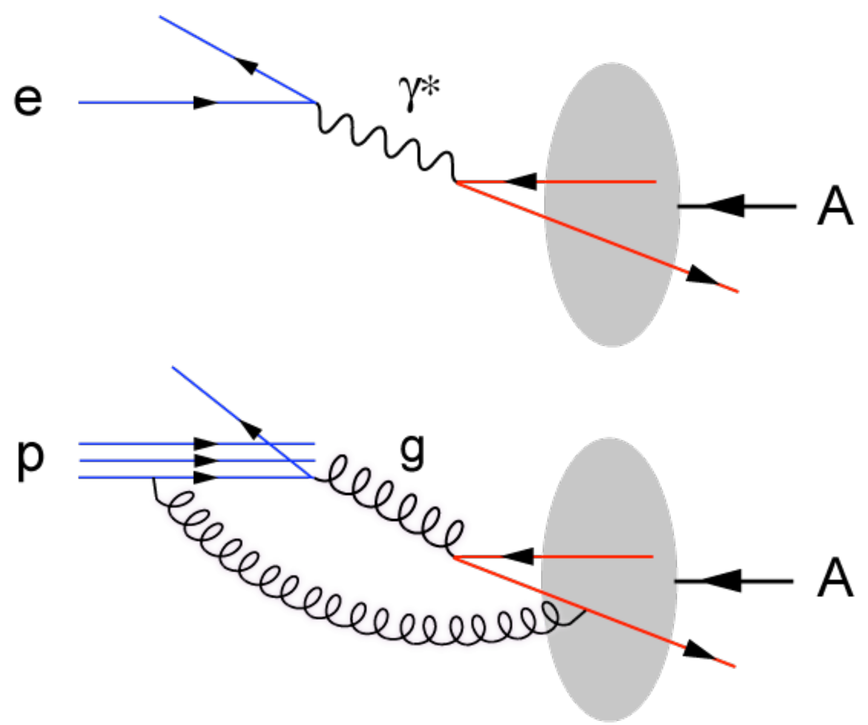


arXiv:1212.1701

Why e+A collisions and not p+A?

- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions
- Both are complementary and offer the opportunity to perform stringent checks of factorization/universality
- Issues:
  - ➡ p+A combines initial and final state effects
  - ➡ multiple colour interactions in p+A
  - ➡ p+A lacks the direct access to x, Q^2



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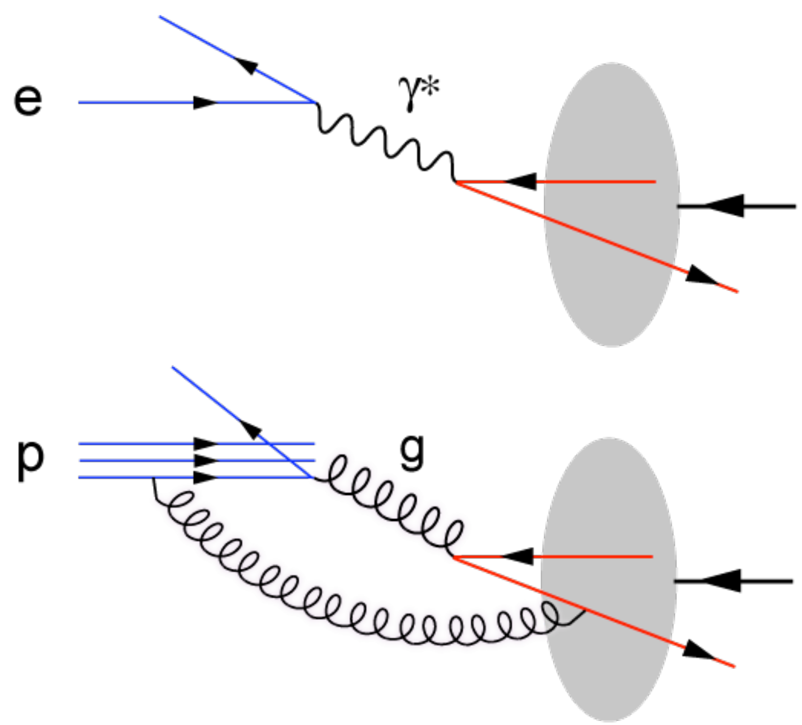

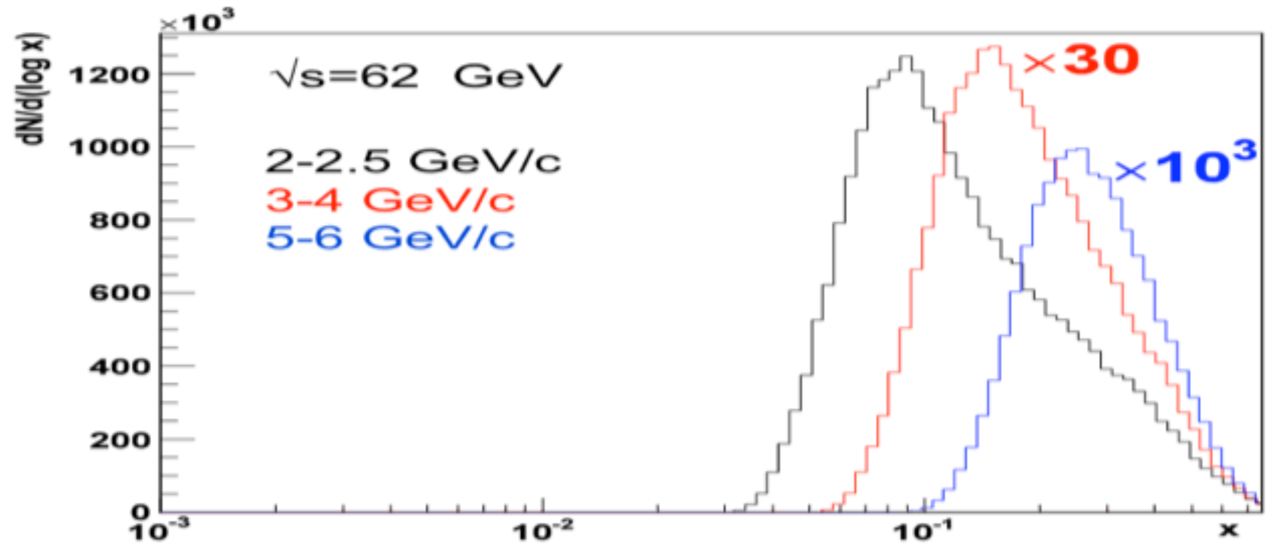

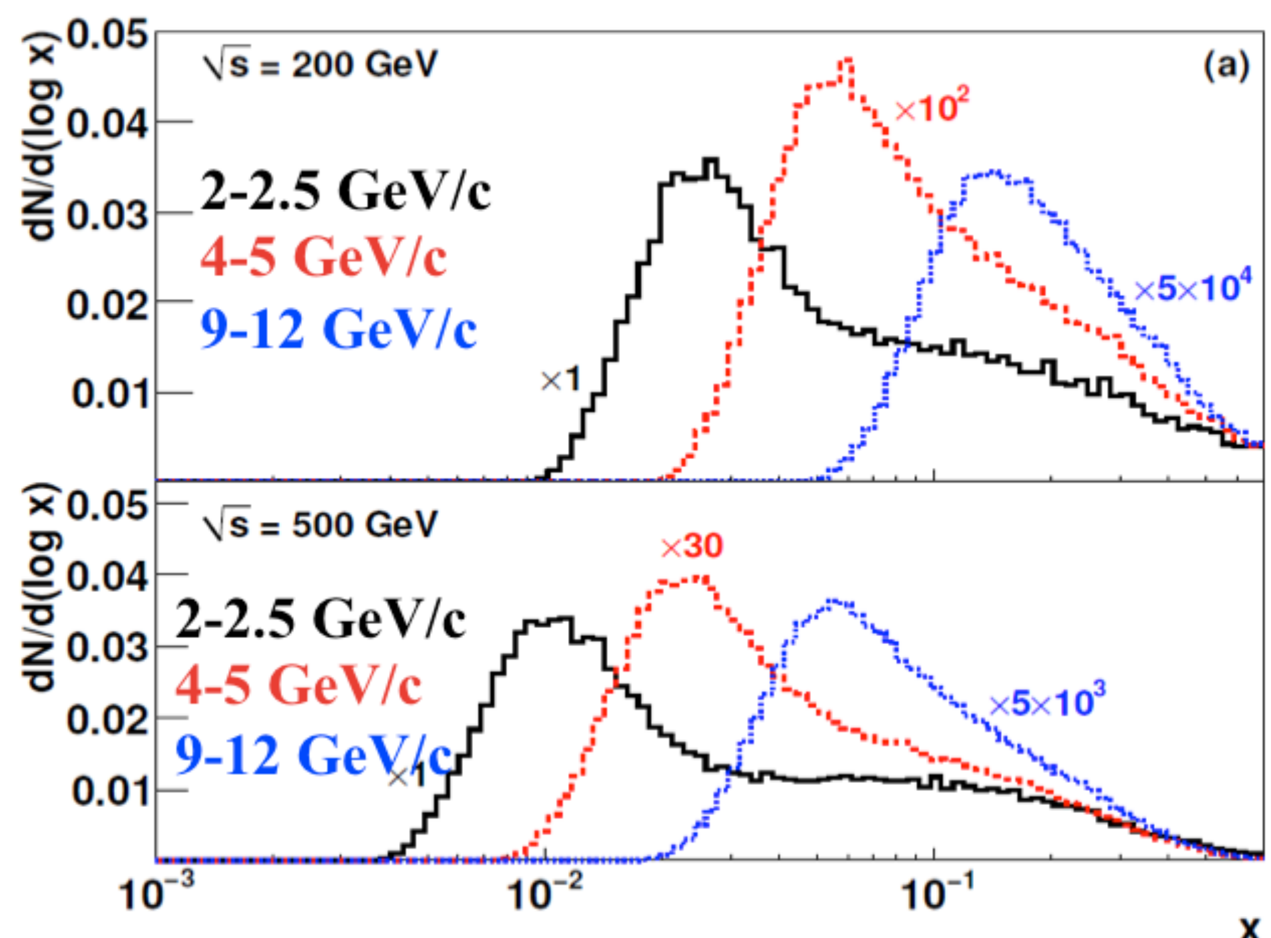

p_T - x correlation in p+p

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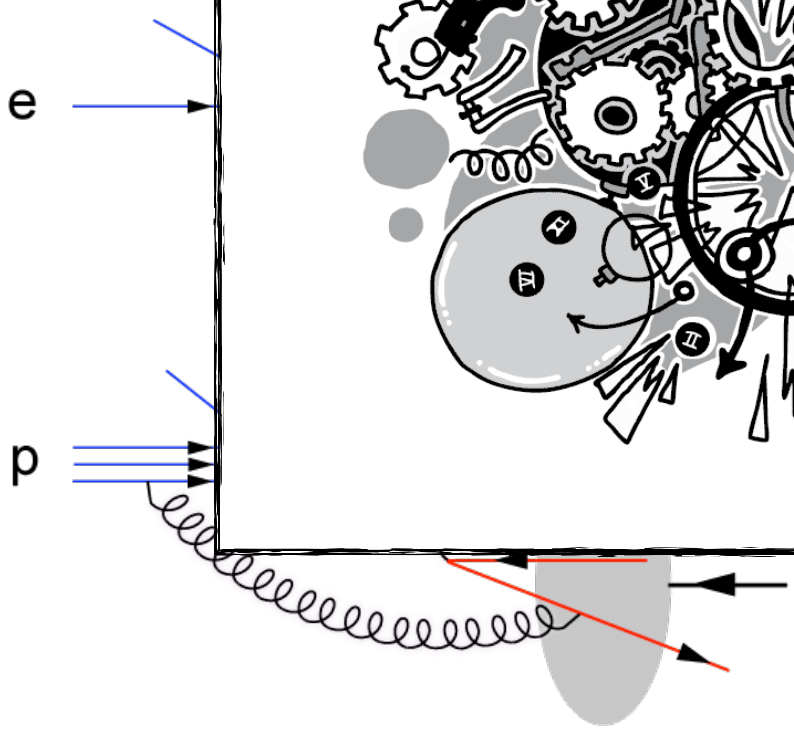
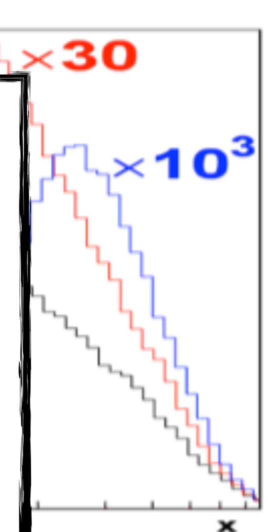
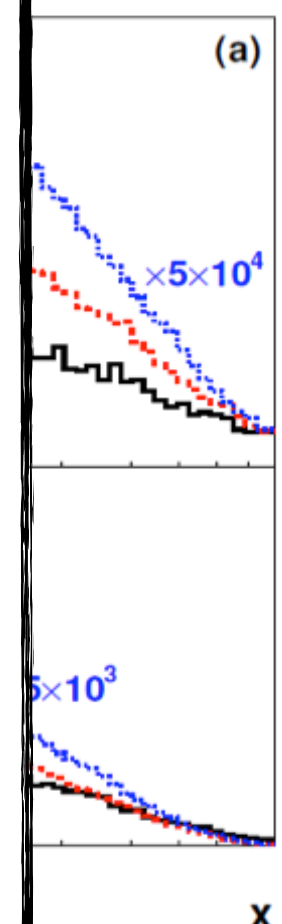






p_T - x correlation in p+p

Scattering of protons on protons
is like colliding Swiss watches to find out how they are built.

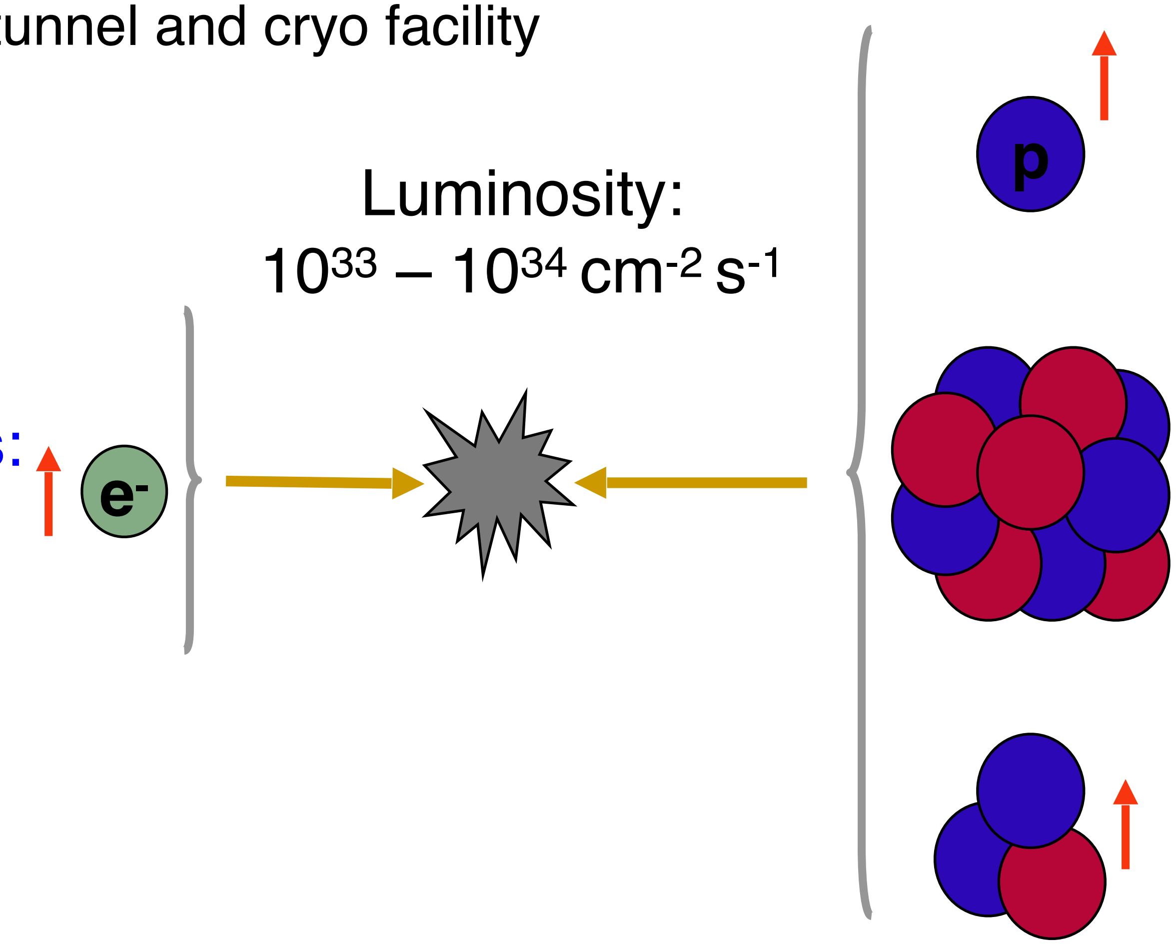
R. Feynman

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC including existing RHIC tunnel and cryo facility

Luminosity: $10^{33} – 10^{34}$ cm^{-2} s^{-1}

80% polarized electrons: 6.6 – 21.2 GeV

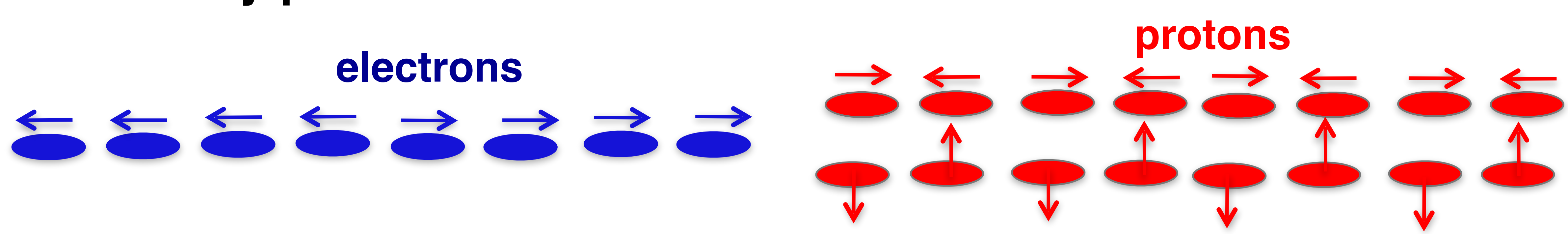


70% polarized protons 25 - 250 (275*) GeV

Light ions (d, Si, Cu) Heavy ions (Au, U) 10 - 100 (110*) GeV/u

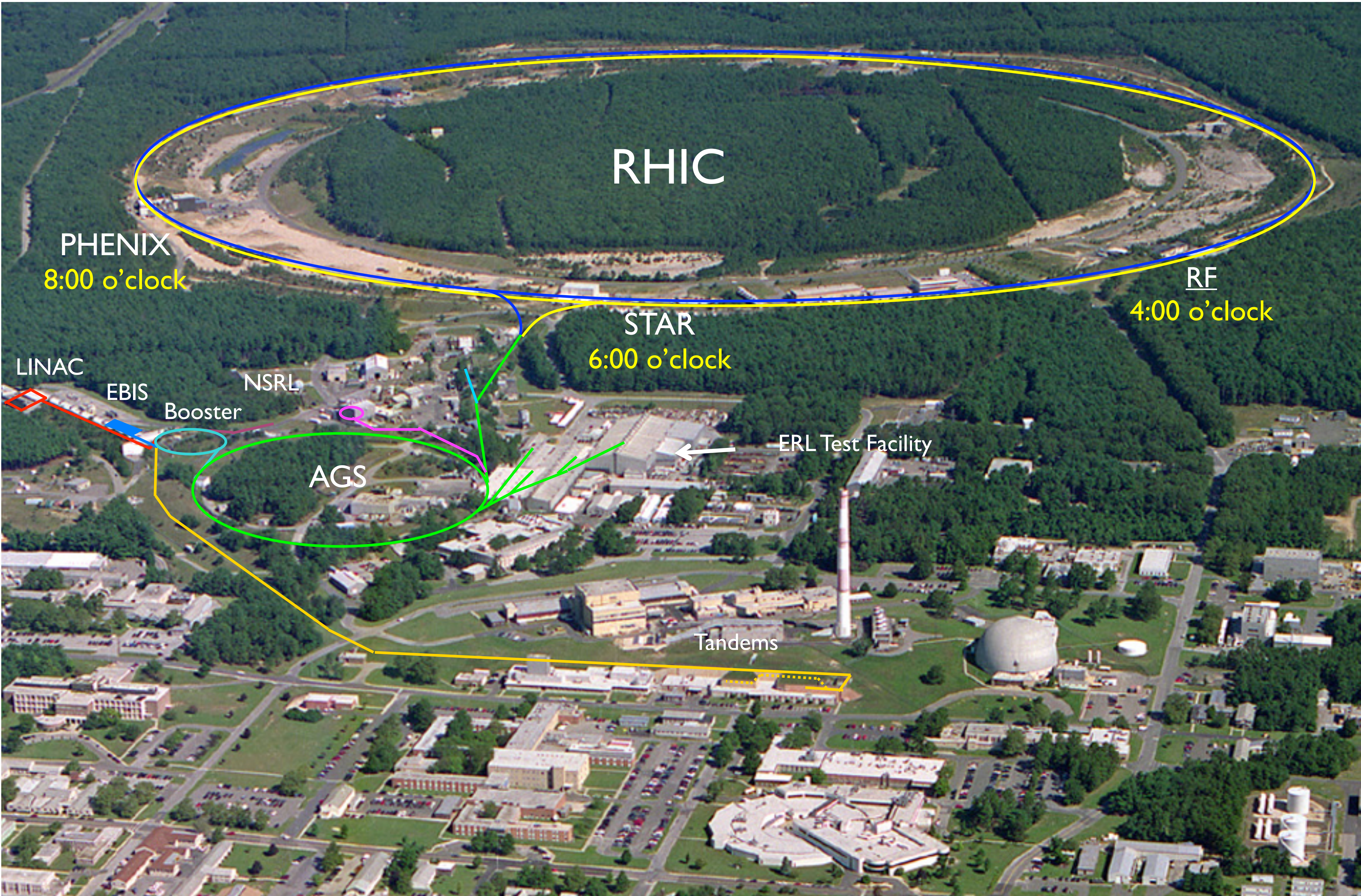
Pol. light ions (He-3) 17 - 167 (184*) GeV/u

Center-of-mass energy range: 30 – 145 GeV
Any polarization direction in electron-hadron collisions



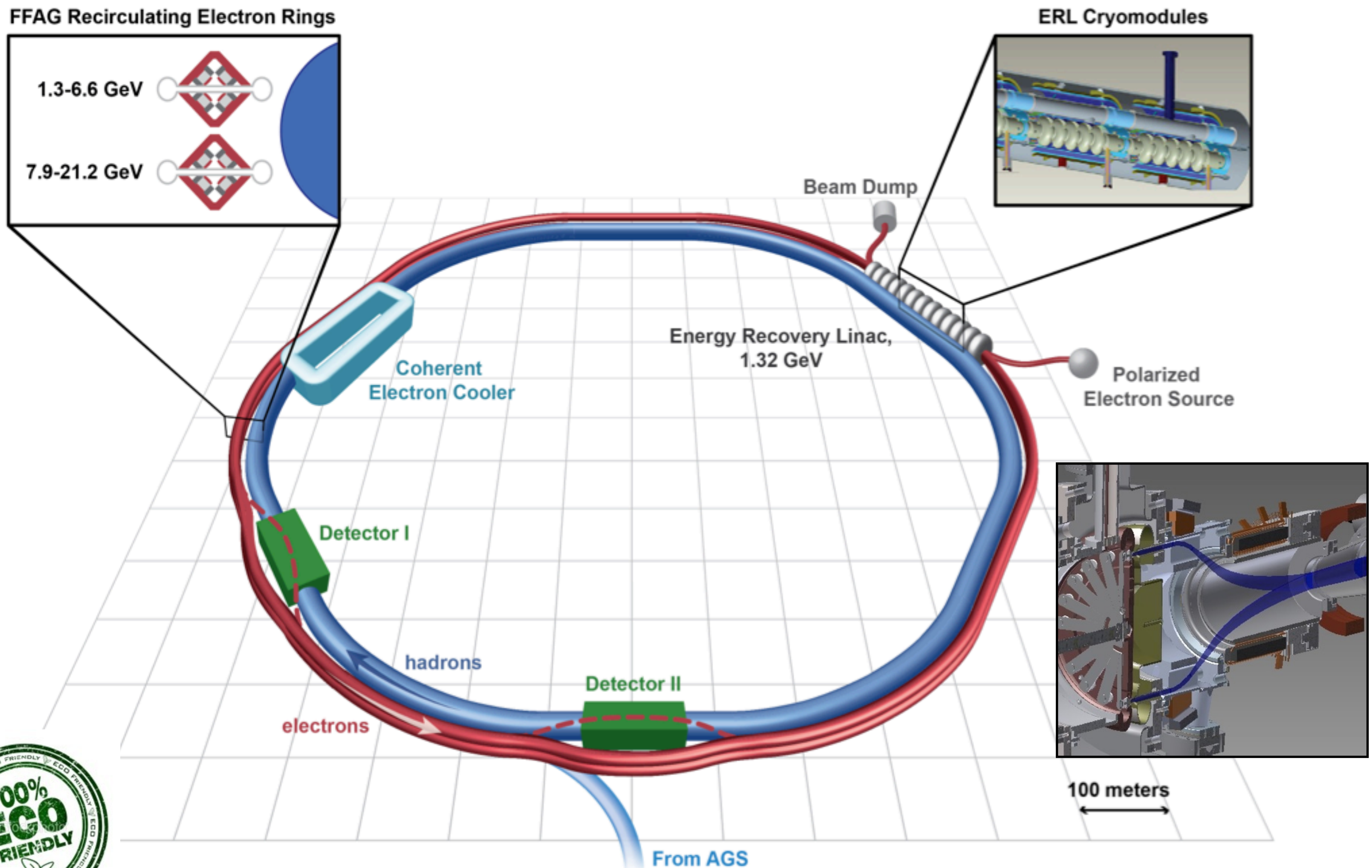
*** It is possible to increase RHIC ring energy by 10%**

From RHIC to eRHIC



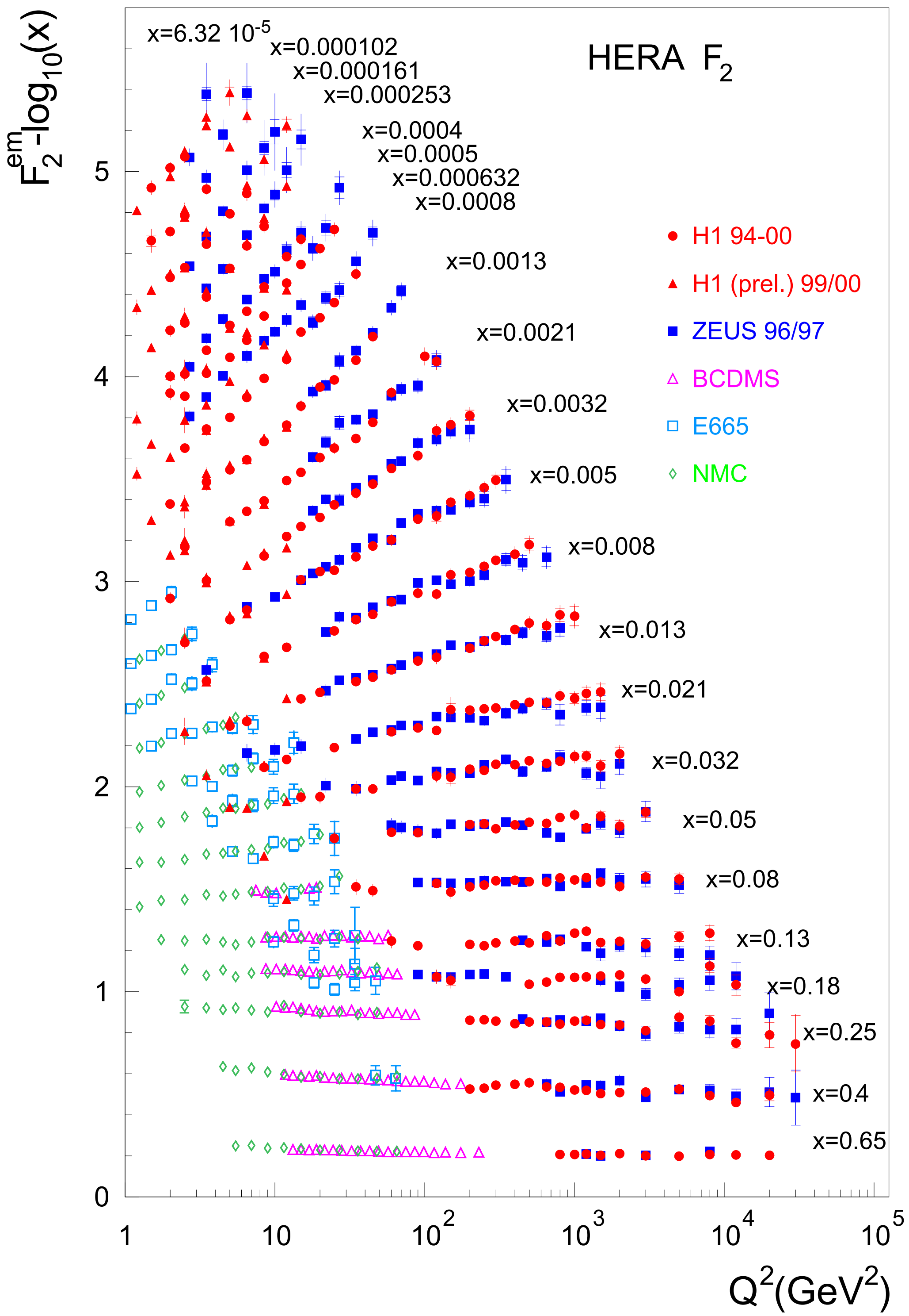
From RHIC to eRHIC

eRHIC design with E_e = 21.2 GeV



What did we learn from e+p collisions at HERA?

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y^+} F_L^A(x, Q^2)$$



quark+anti-quark momentum distributions

gluon momentum distribution

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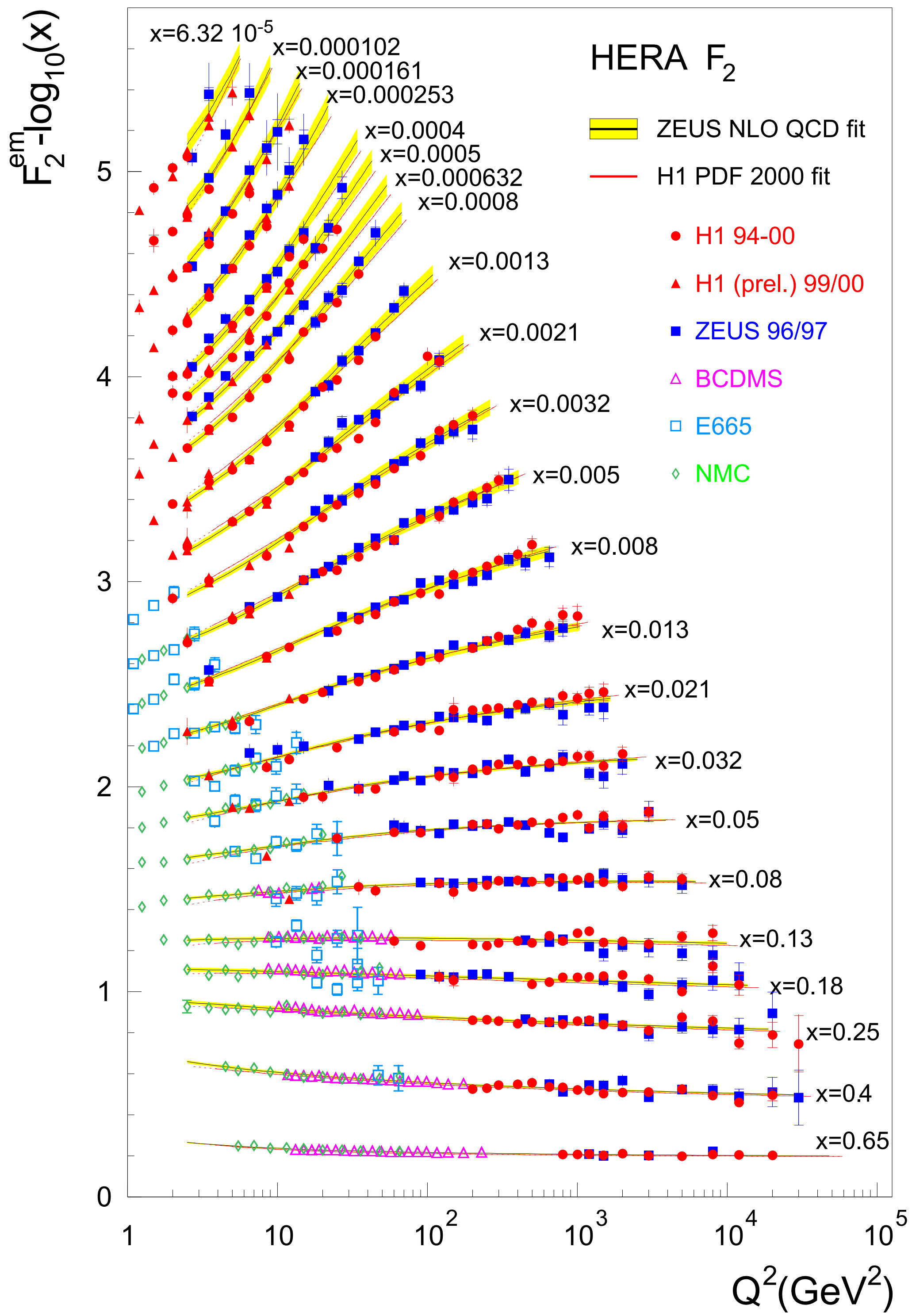

Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution $\Rightarrow$ $G(x,Q^2)$

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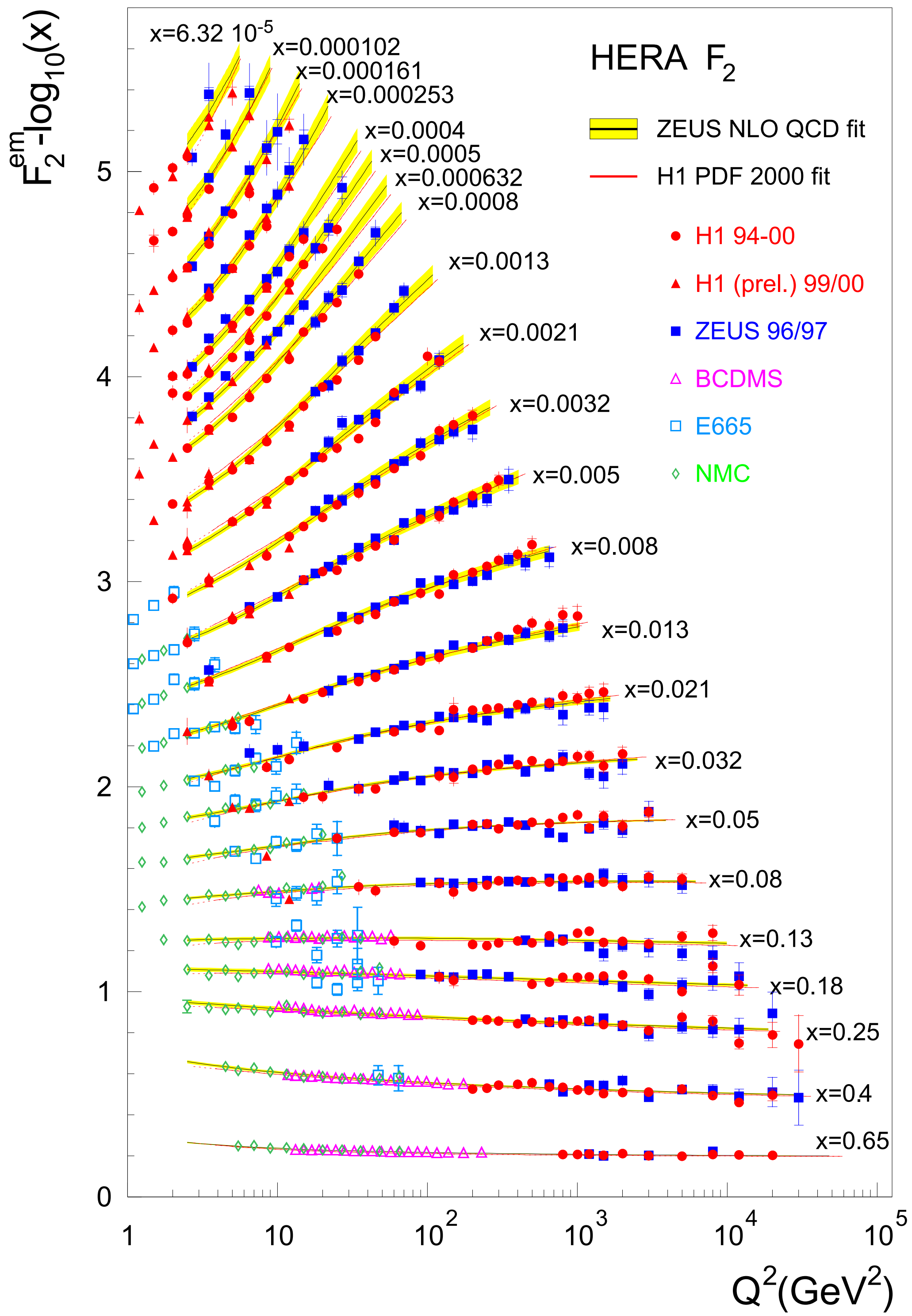

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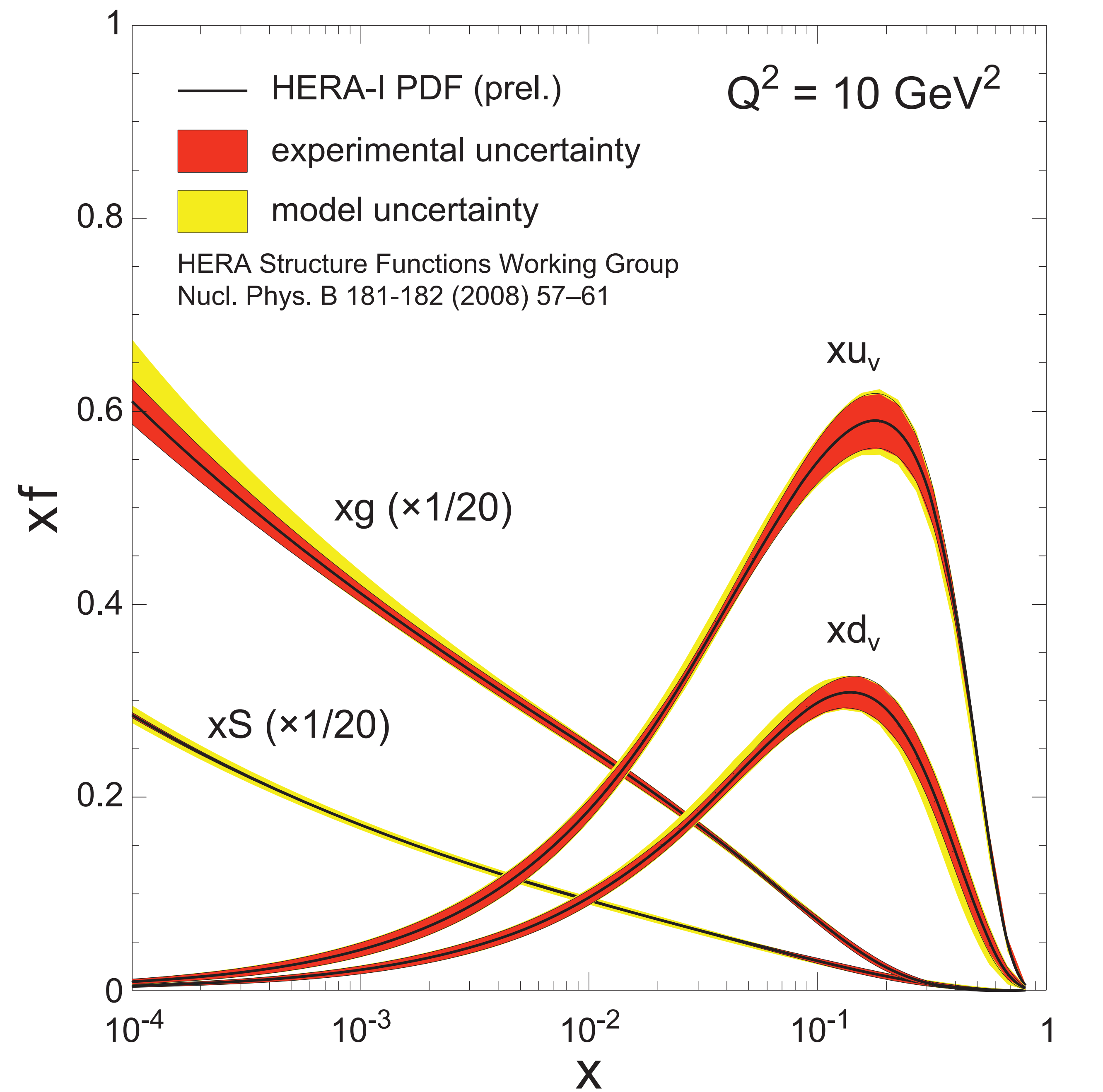

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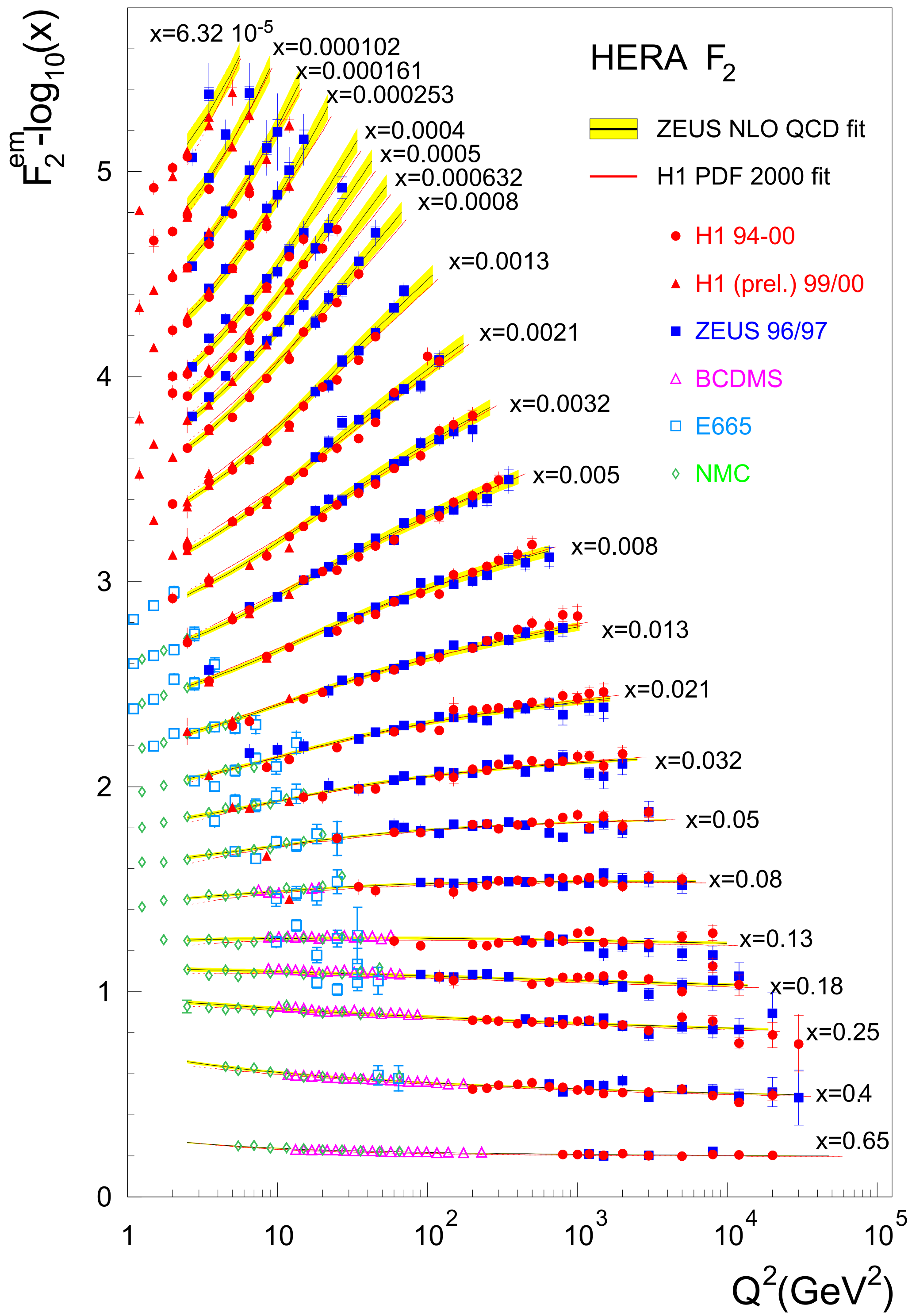

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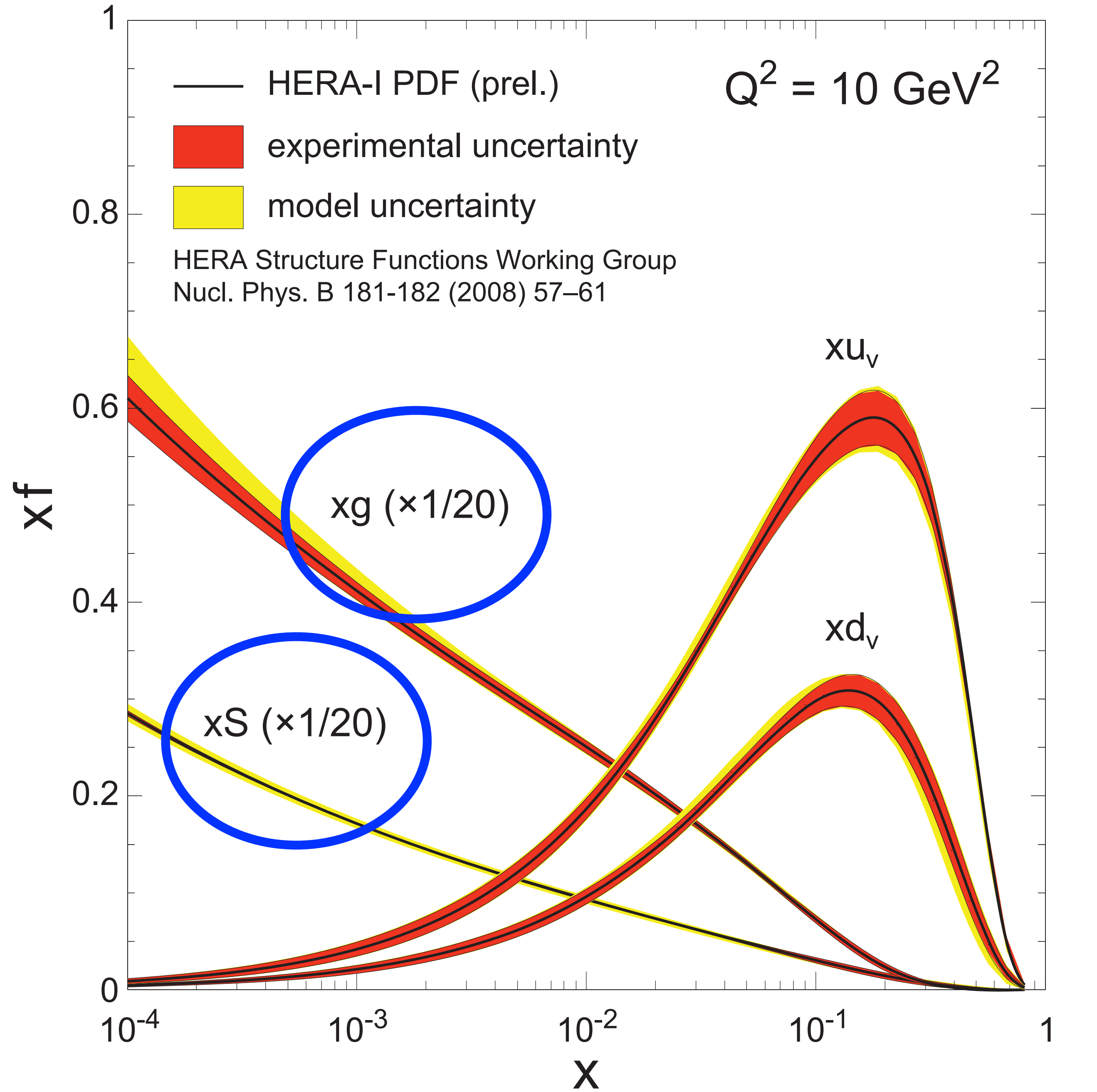

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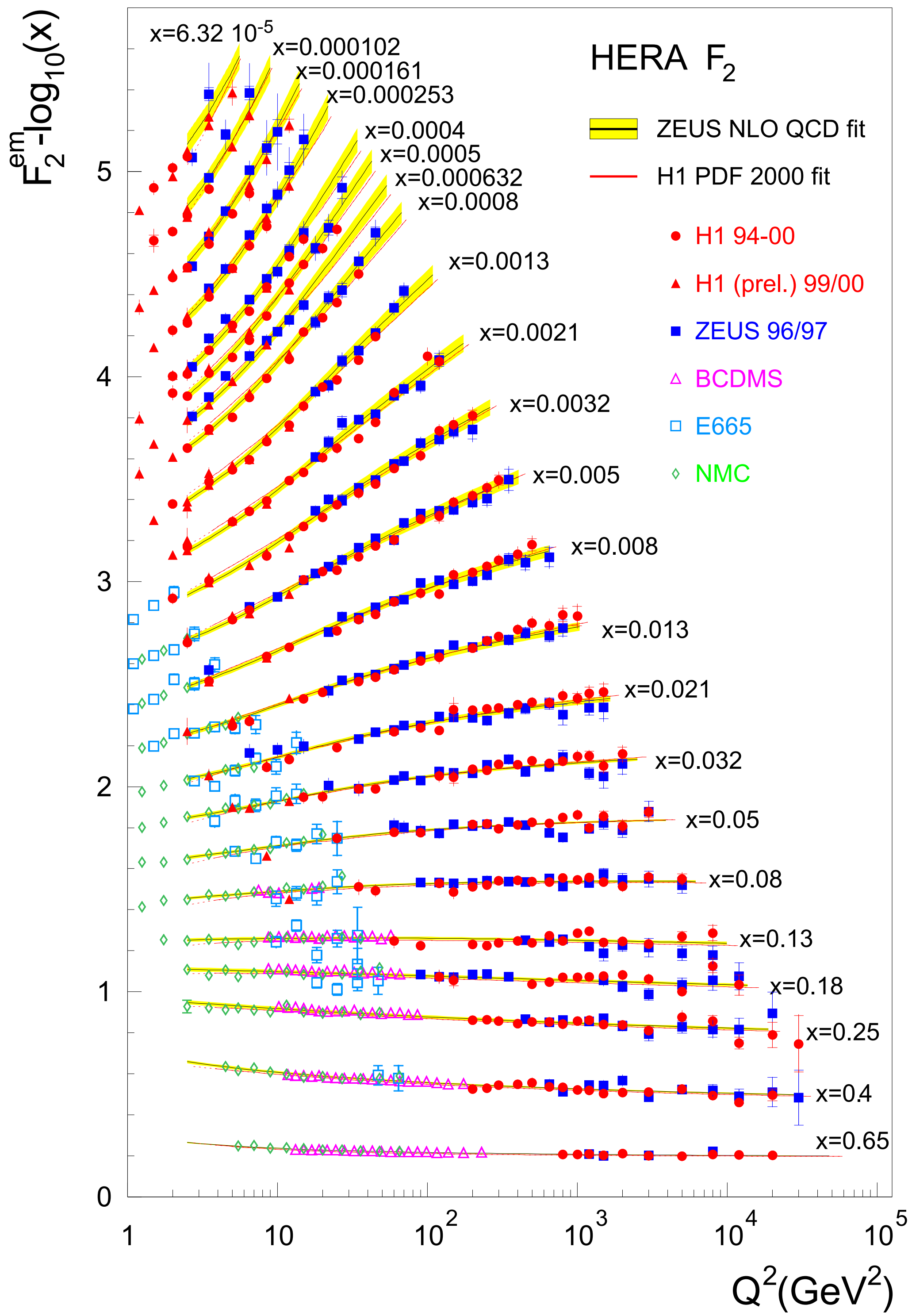

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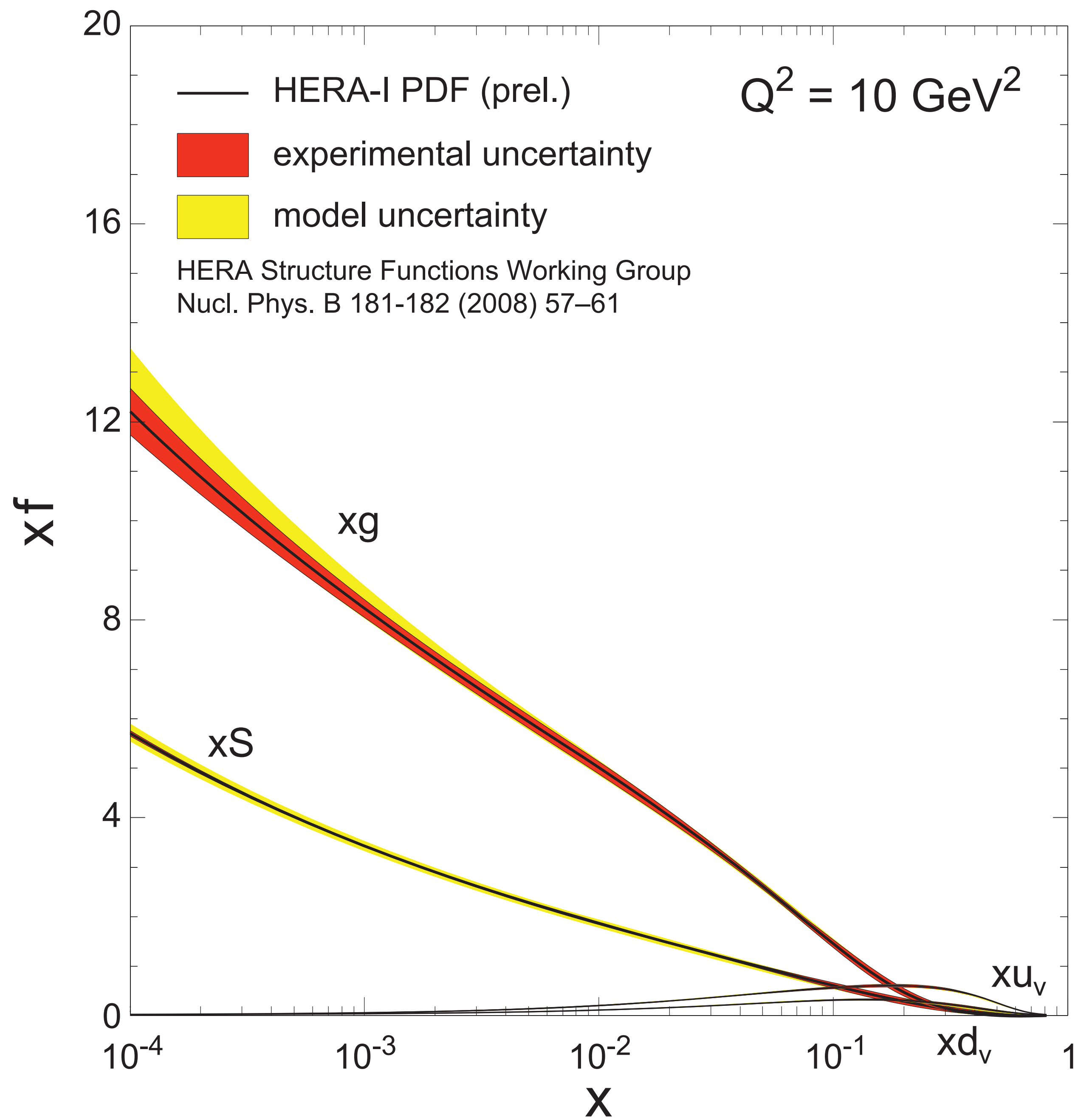
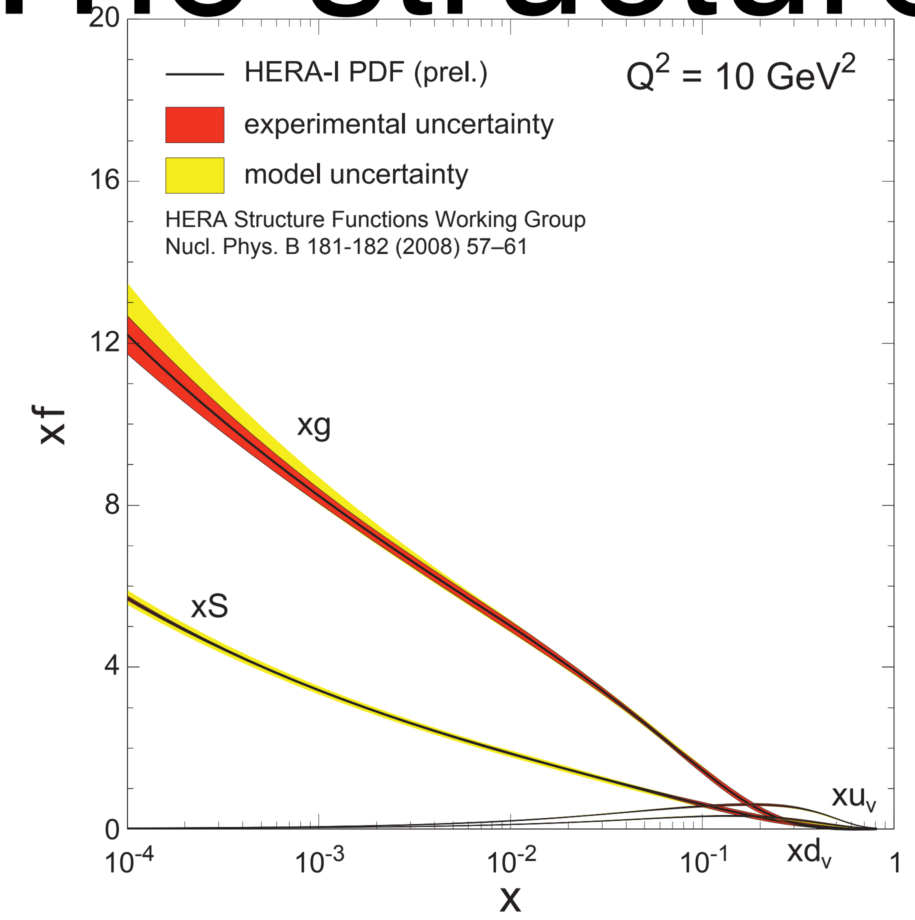
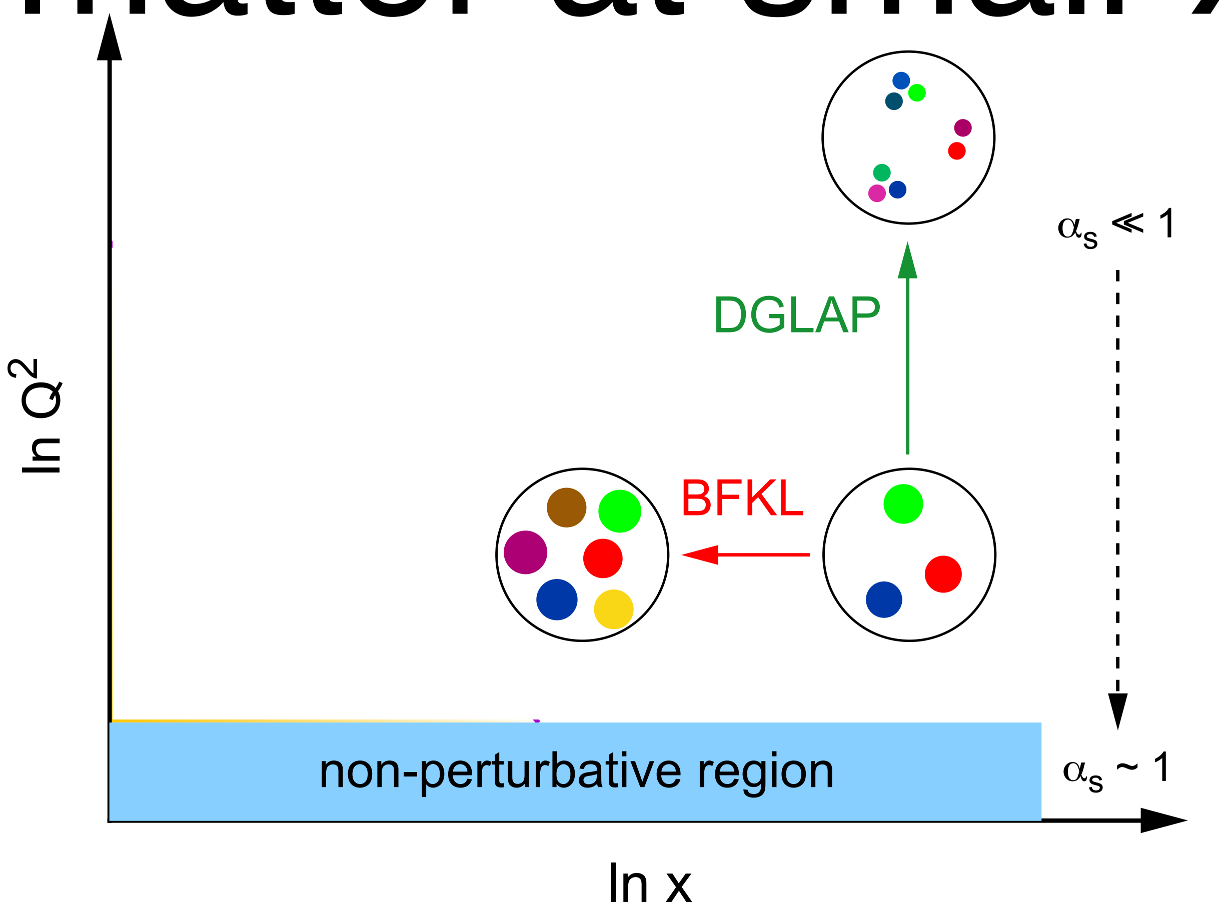


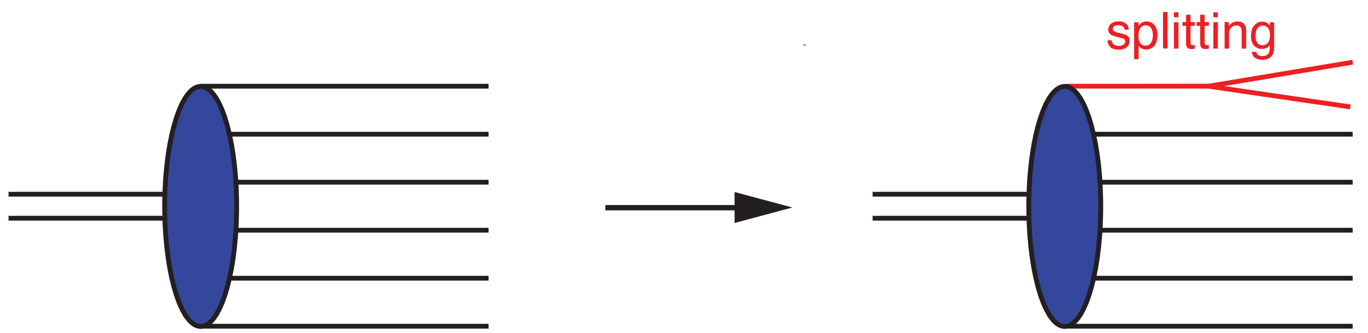
The structure of matter at small-x





- Gluons dominate the PDFs at small- to intermediate-x (x < 0.1)

  ➡Rapid rise in gluons described naturally by linear pQCD evolution equations



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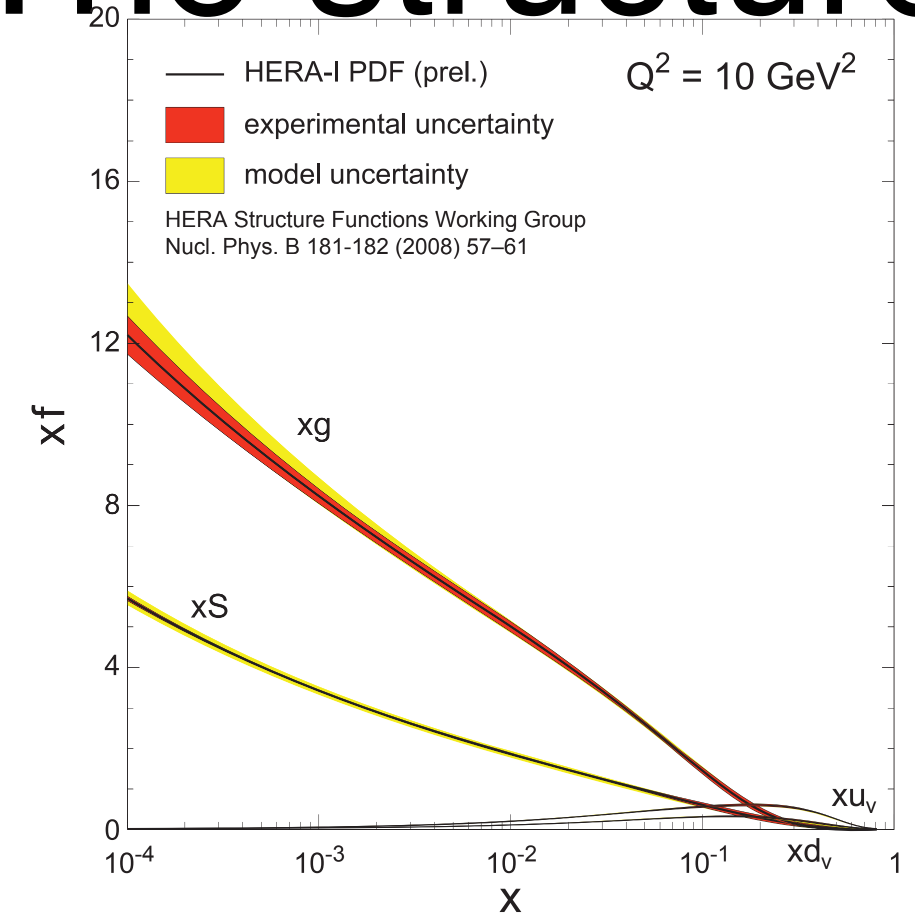
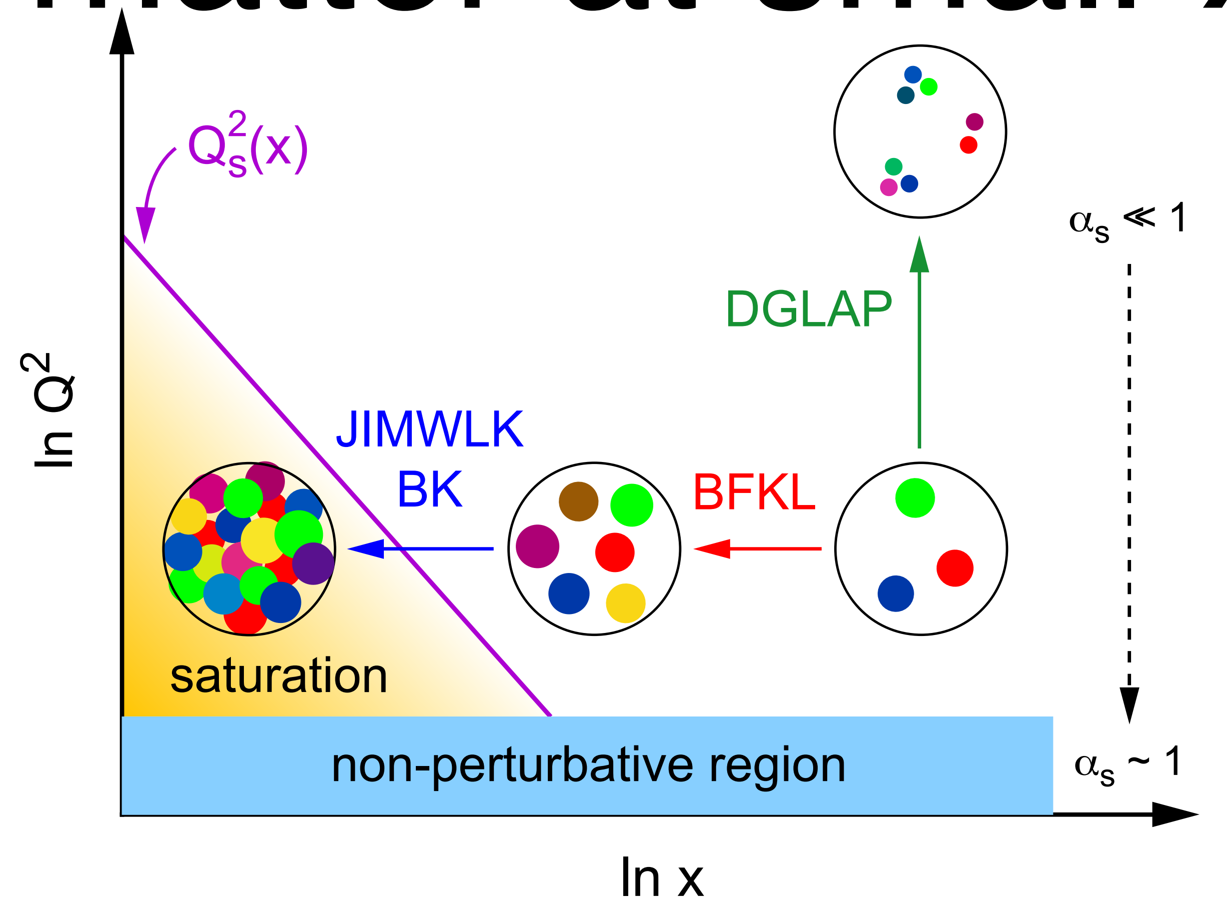
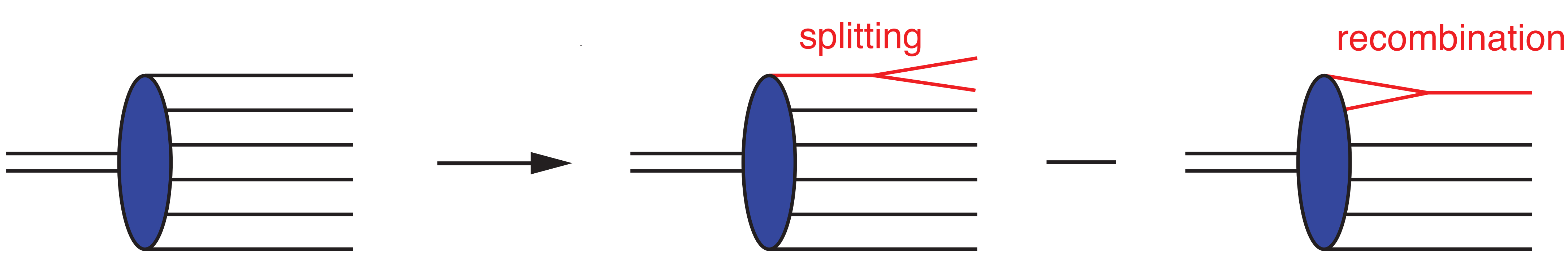




- Gluons dominate the PDFs at small- to intermediate-x (x < 0.1)
  - ➡ Rapid rise in gluons described naturally by linear pQCD evolution equations
  - ➡ This rise cannot increase forever - limits on the cross-section
    - non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation scale $Q^2_S(x)$



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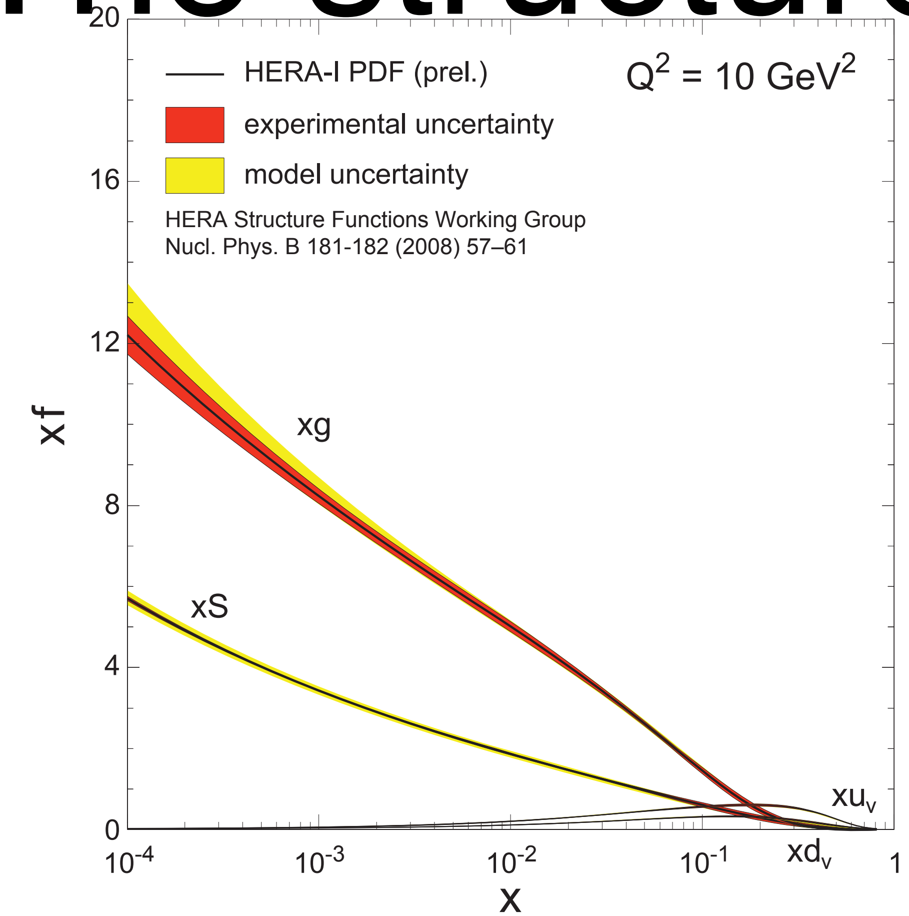

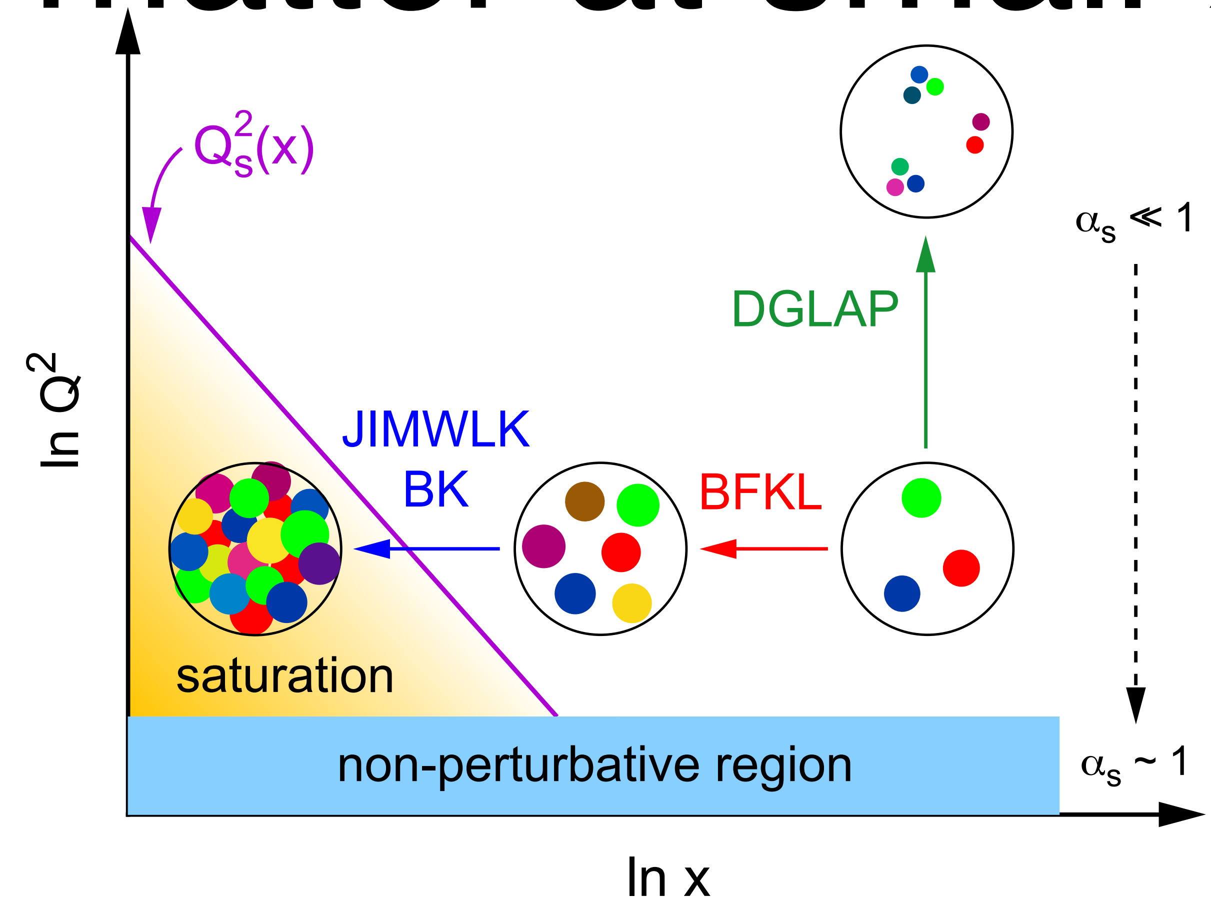

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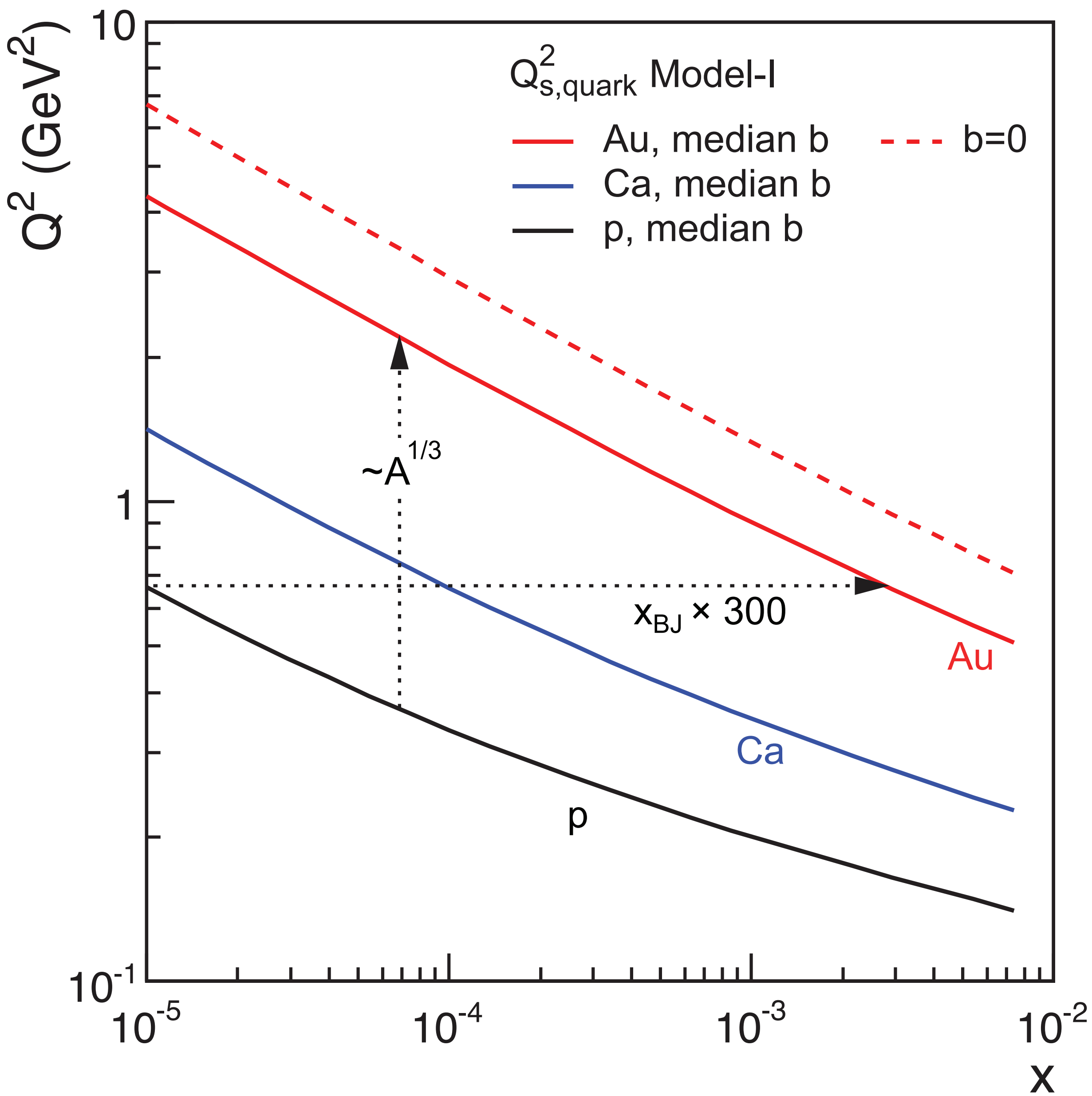
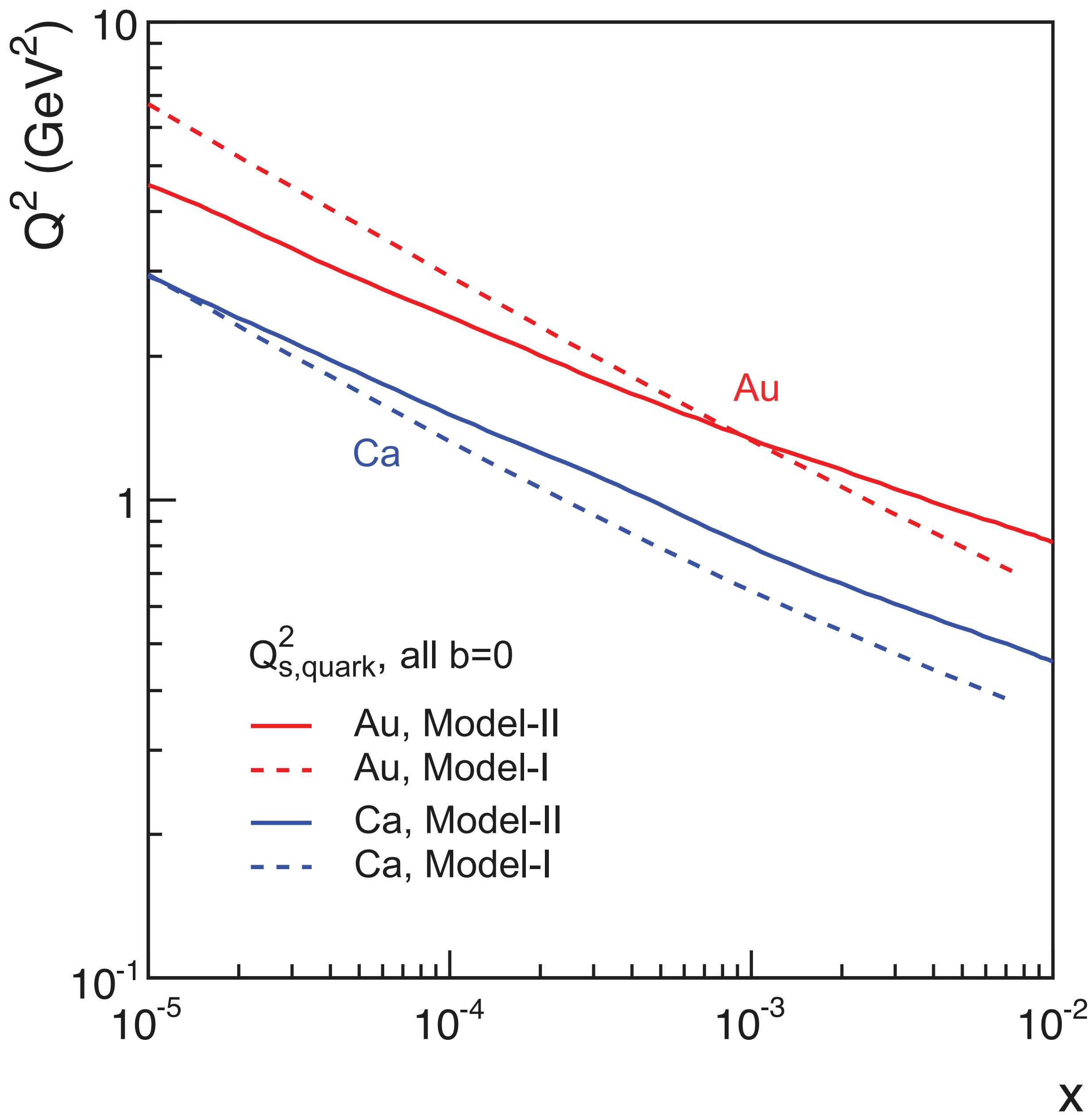
however - saturation in the gluon density is not observed in the gluon distribution at HERA -> too small an x

How can this be observed at eRHIC?

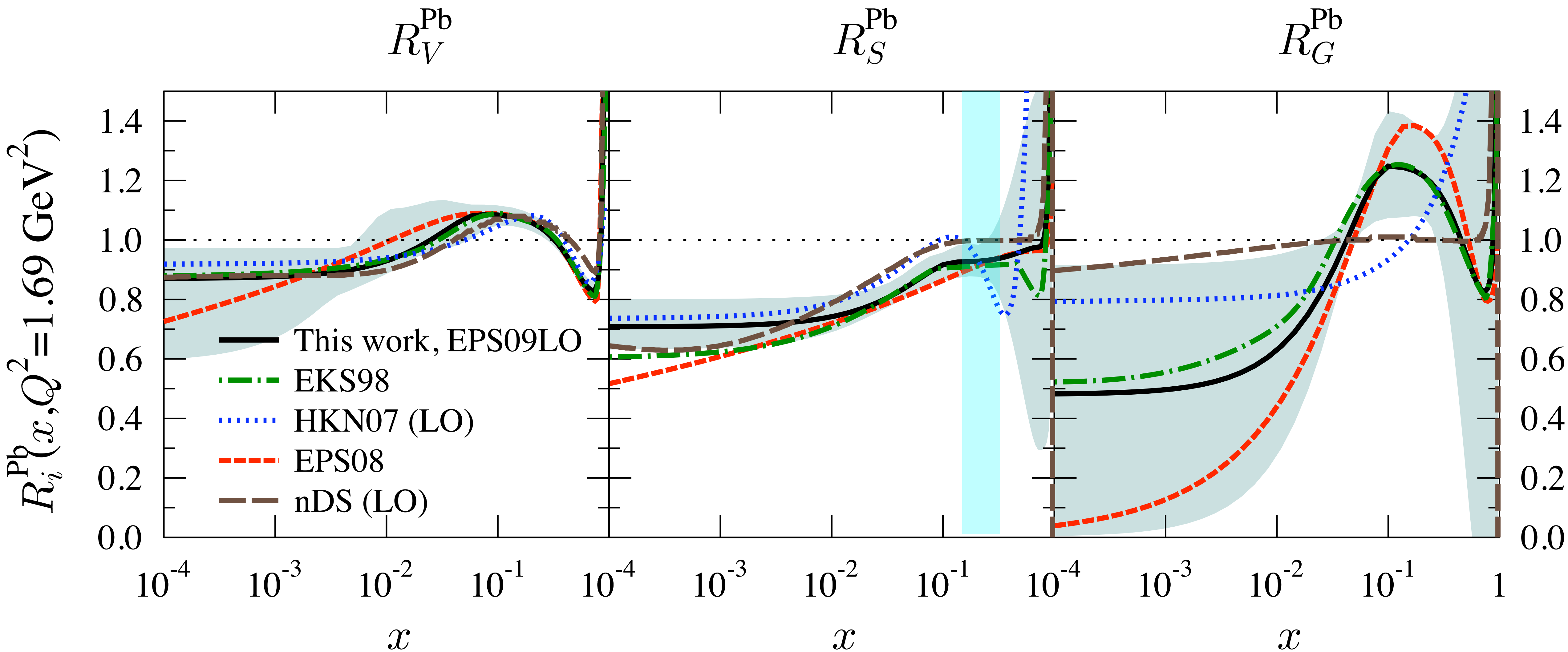
Nuclear "oomph" effect

Pocket formula: $Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$





What do we know about the structure of nuclei?



The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

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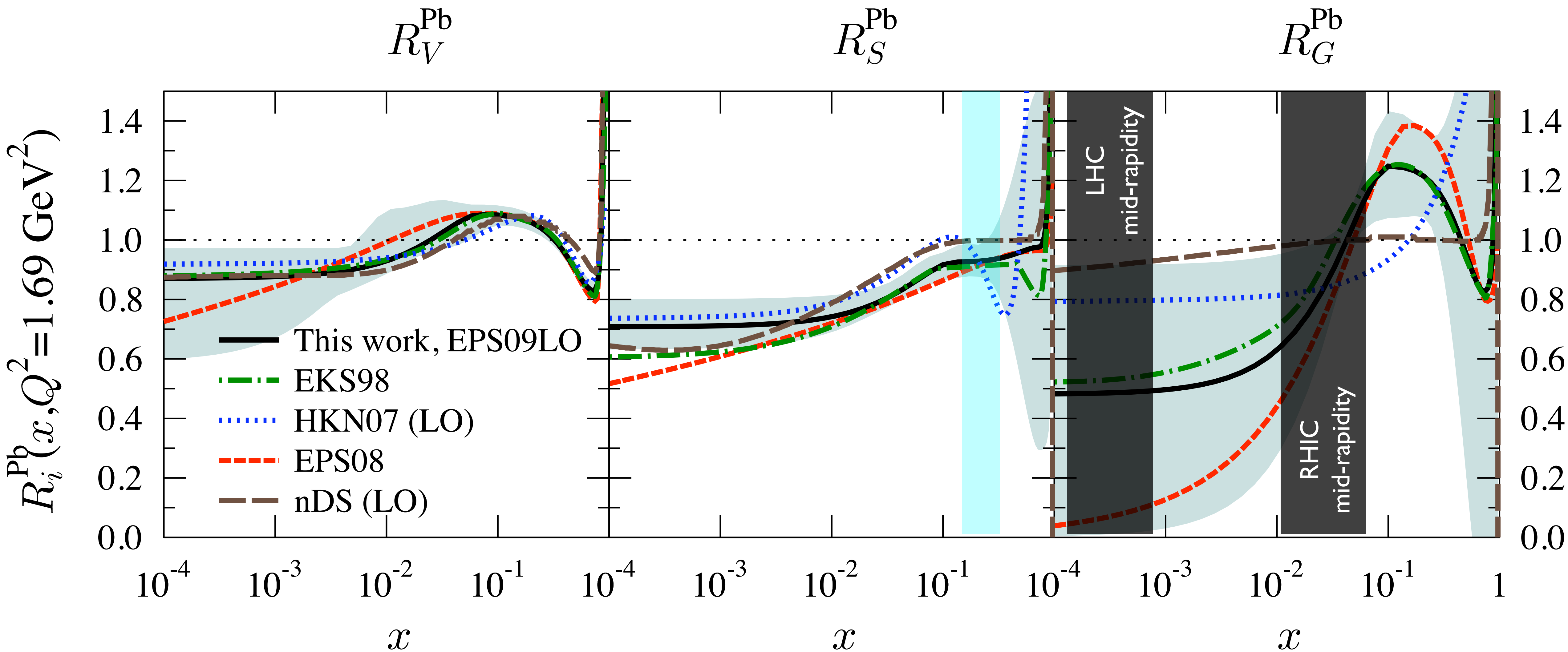

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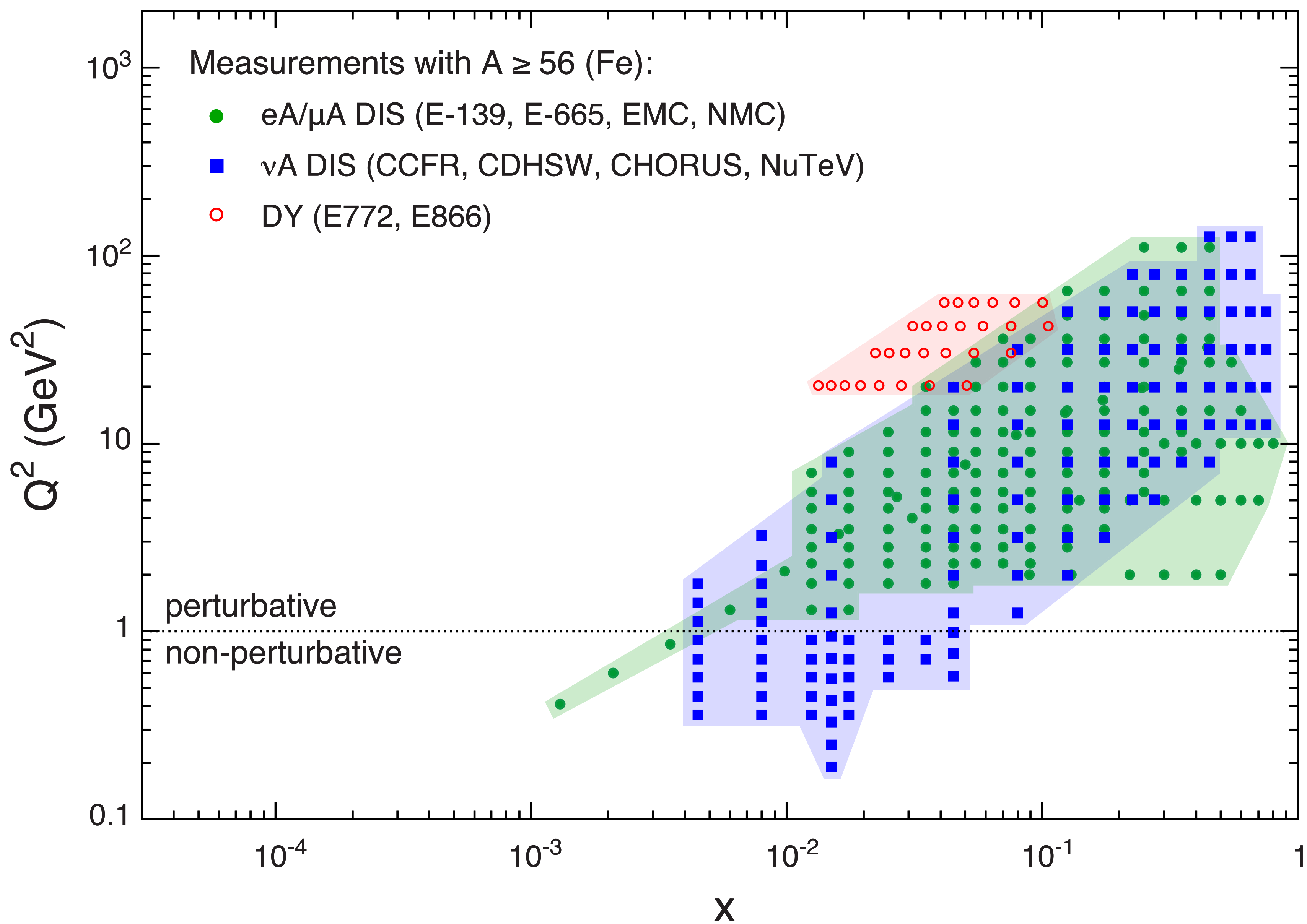
Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

Phase-space coverage of e+A collisions for an EIC

- Existing data:
  - ➡ Low energy (fixed target)
  - ➡ Low statistics
  - ➡ Mainly light A
- EIC coverage:
  - ➡ Both "low energy" and "high energy" options extend the reach in x-Q^2 beyond current data
  - ➡ A coverage extended up to U
  - ➡ Saturation scale at moderate Q^2 can be investigated at the lowest x



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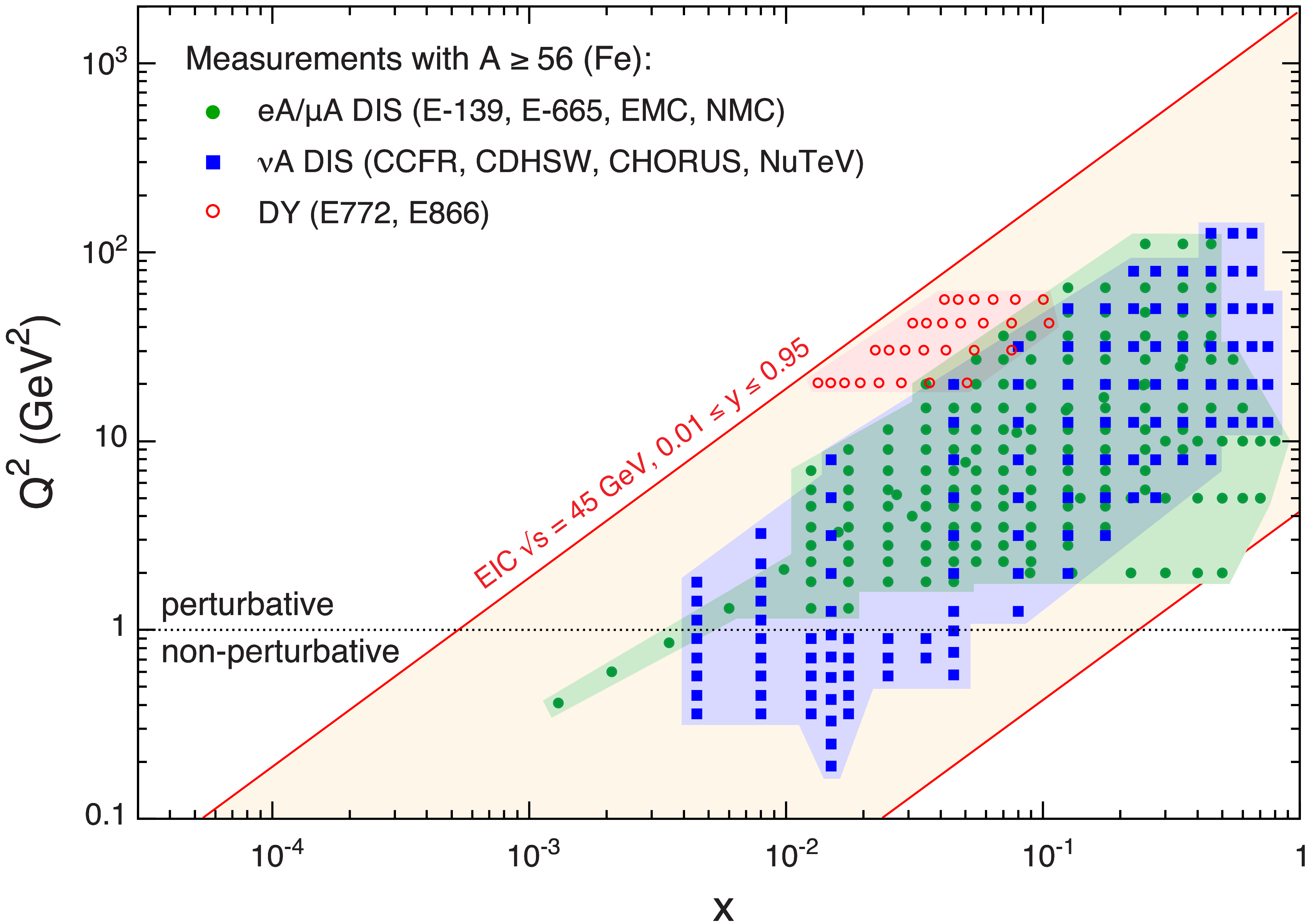

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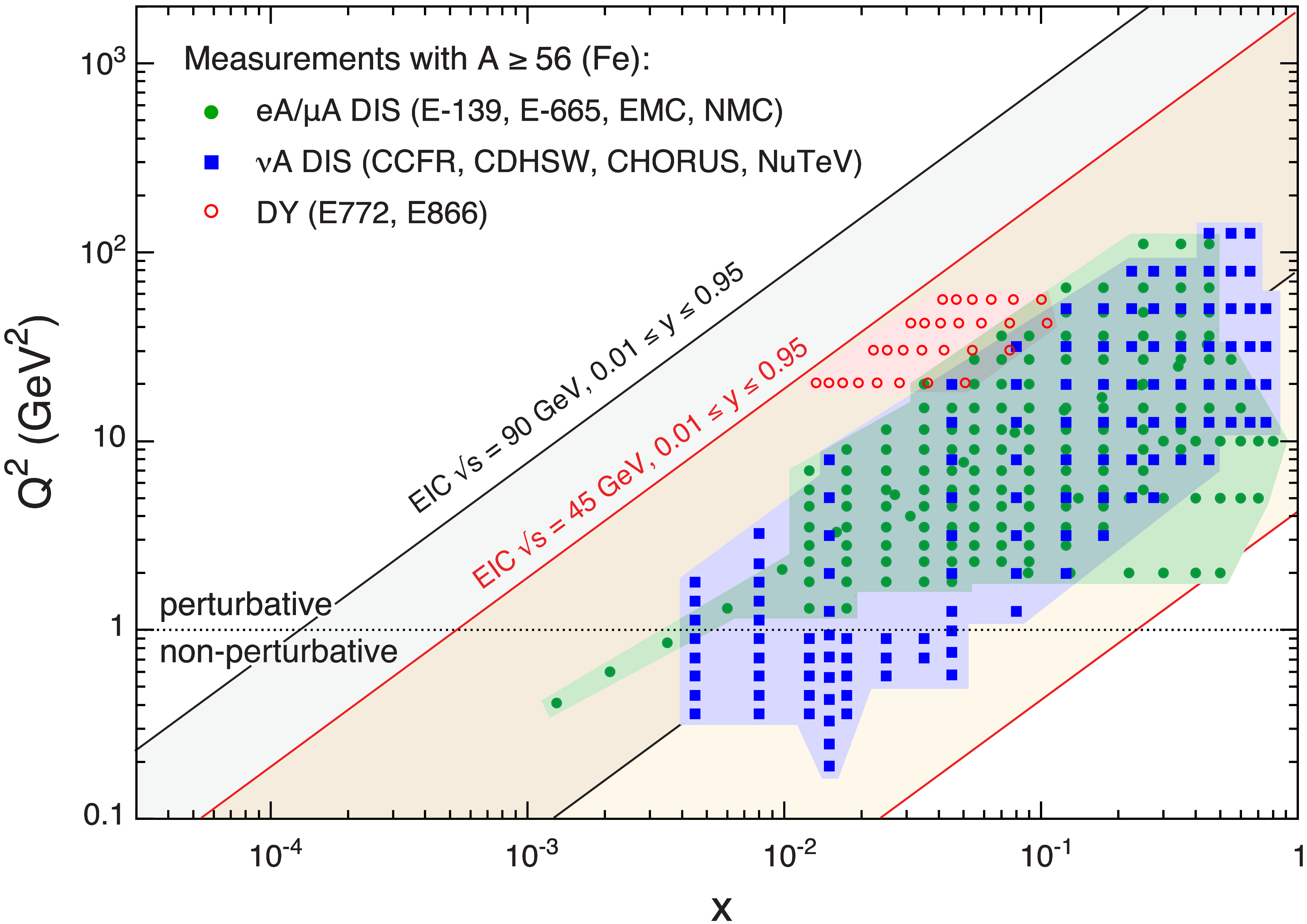

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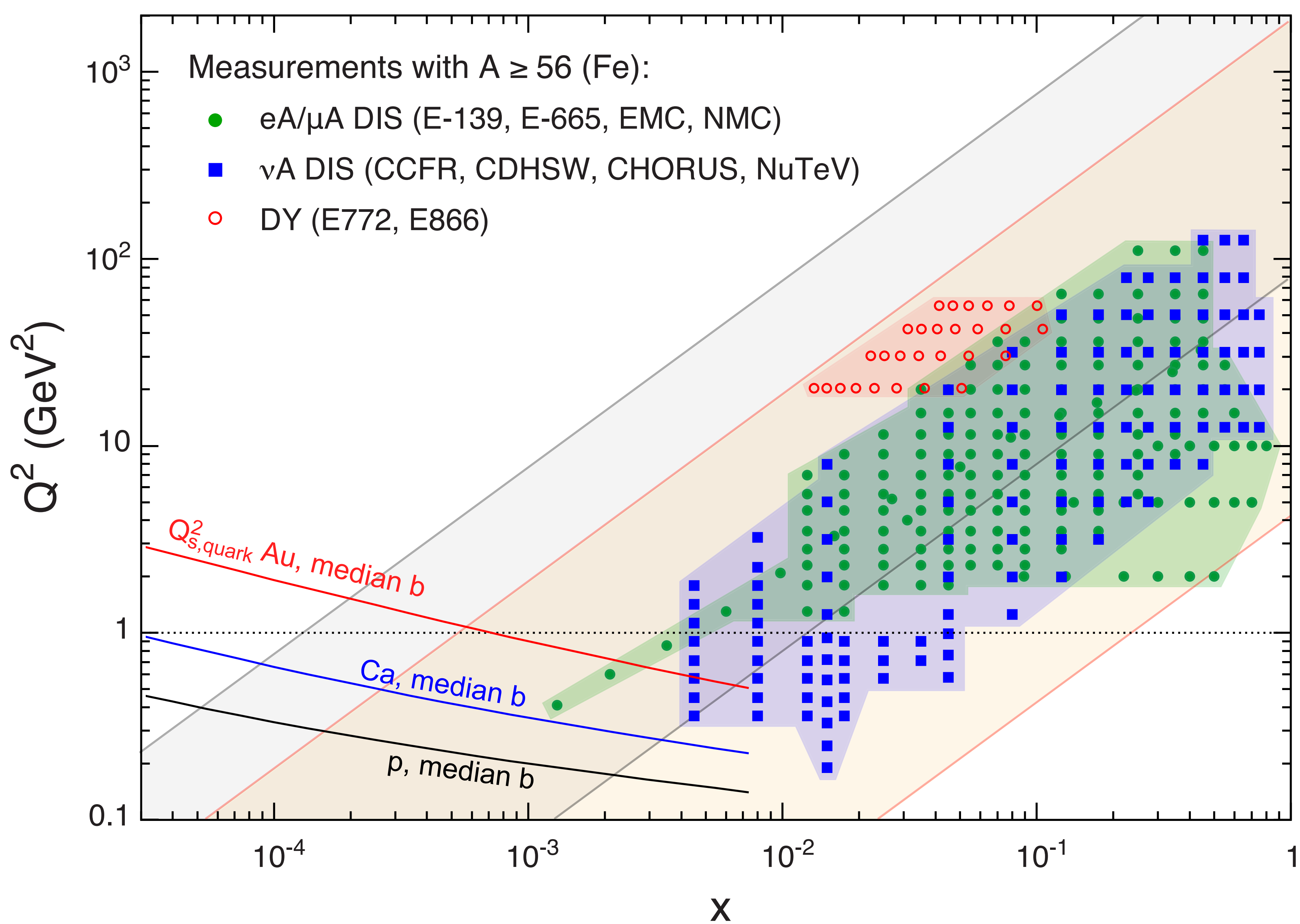


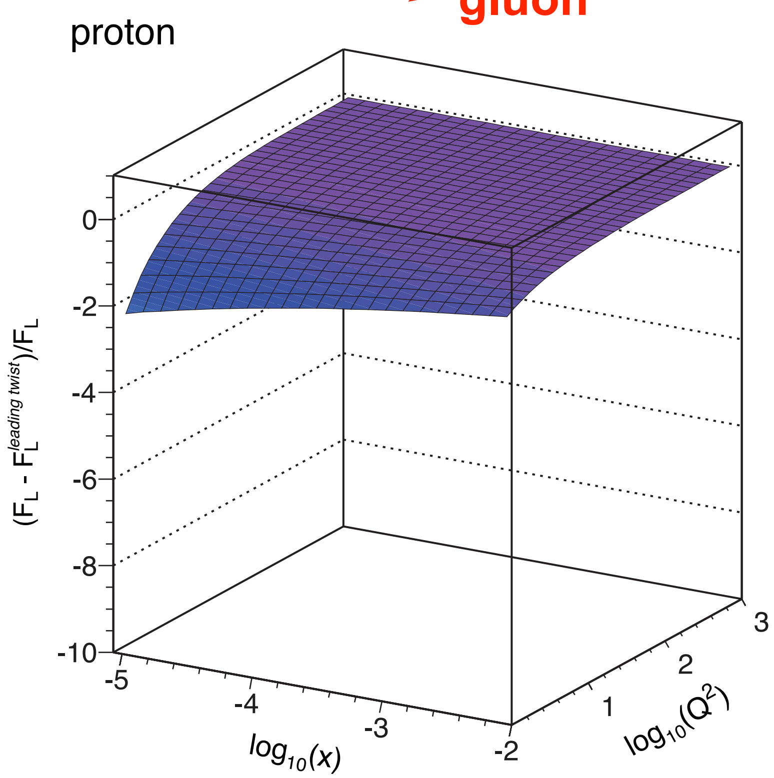
Saturation effects in the proton and nucleus

$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark

gluon

Measure of non-linear effects in the F_L structure function



Dipole model (J. Bartels *et al.*)

- Plotting this distribution coming out of saturation inspired GBW model
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quark+anti-quark (for $F_2(x,Q^2)$)

gluon (for $F_L(x,Q^2)$)

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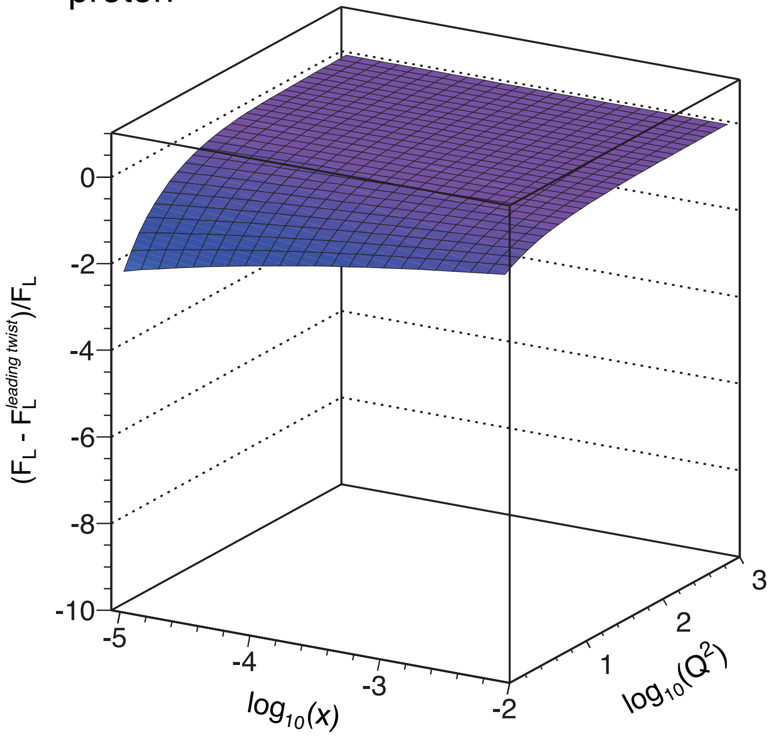

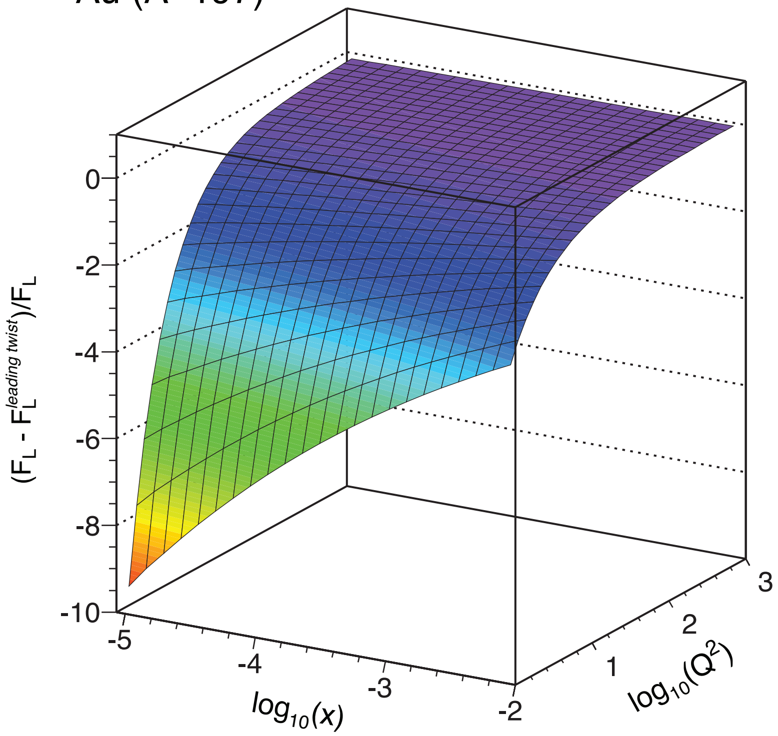

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quark+anti-quark **gluon**

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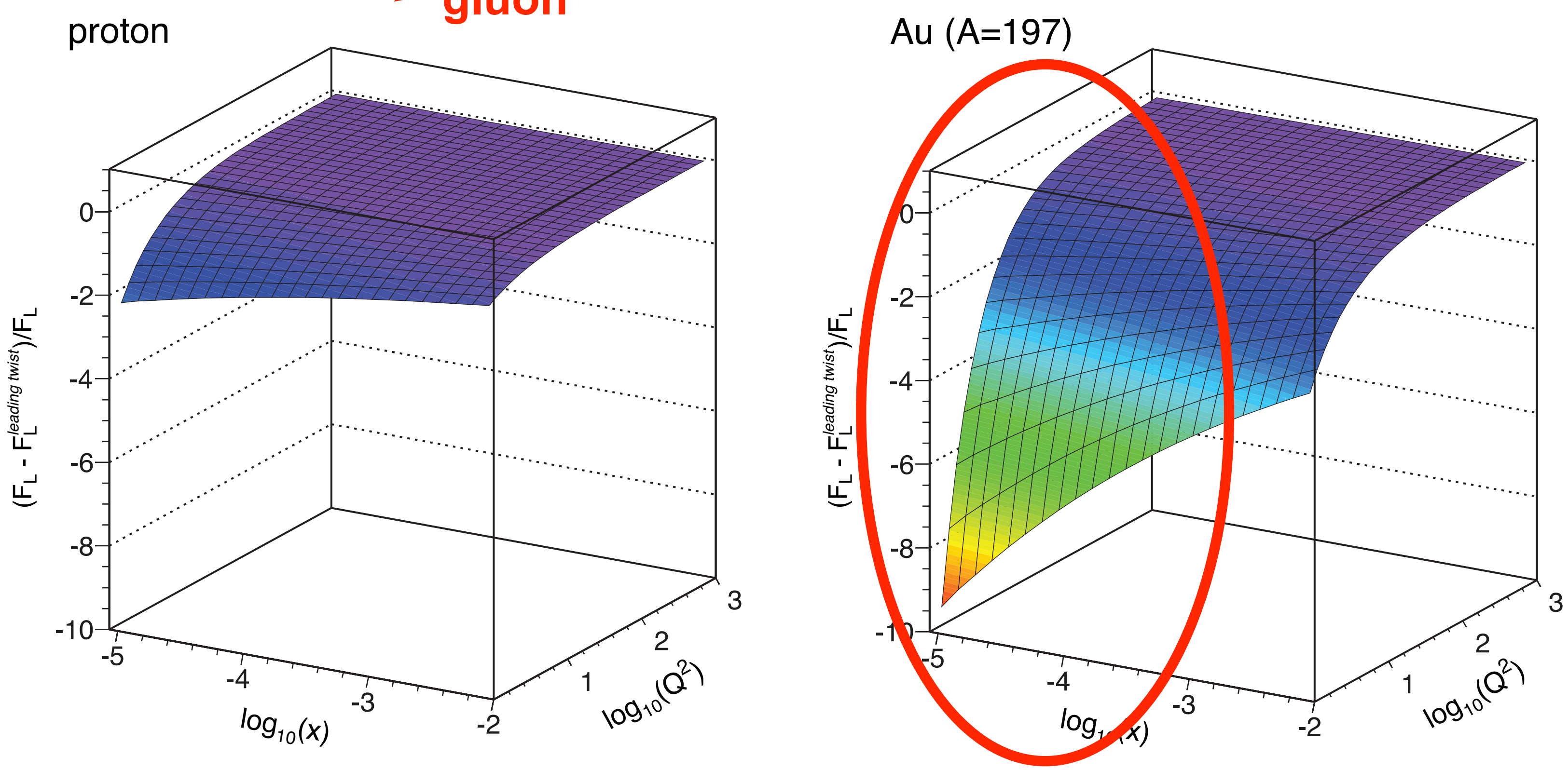

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A precision measurement of the F_2^A nuclear structure function

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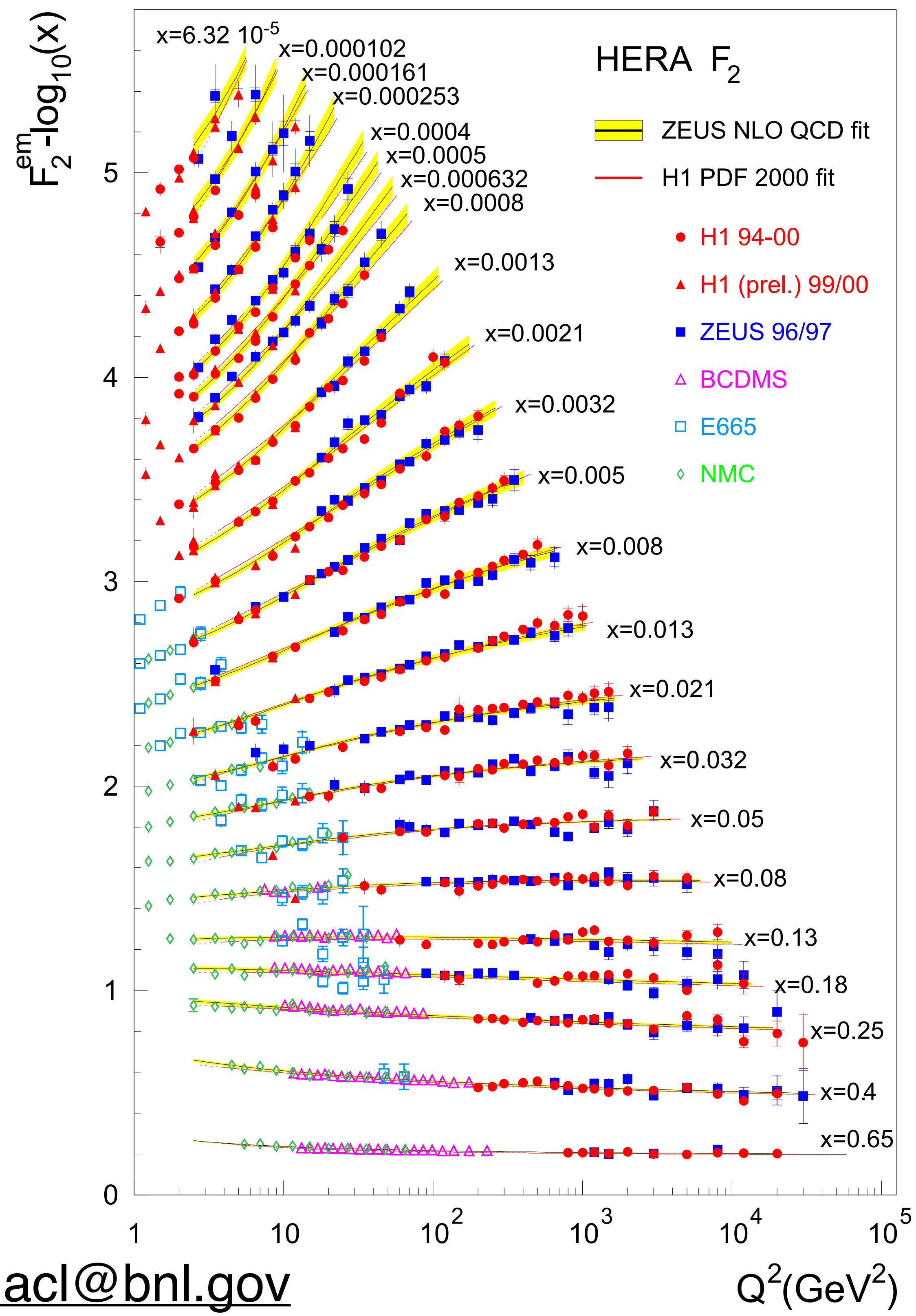

3% systematic errors added in quadrature

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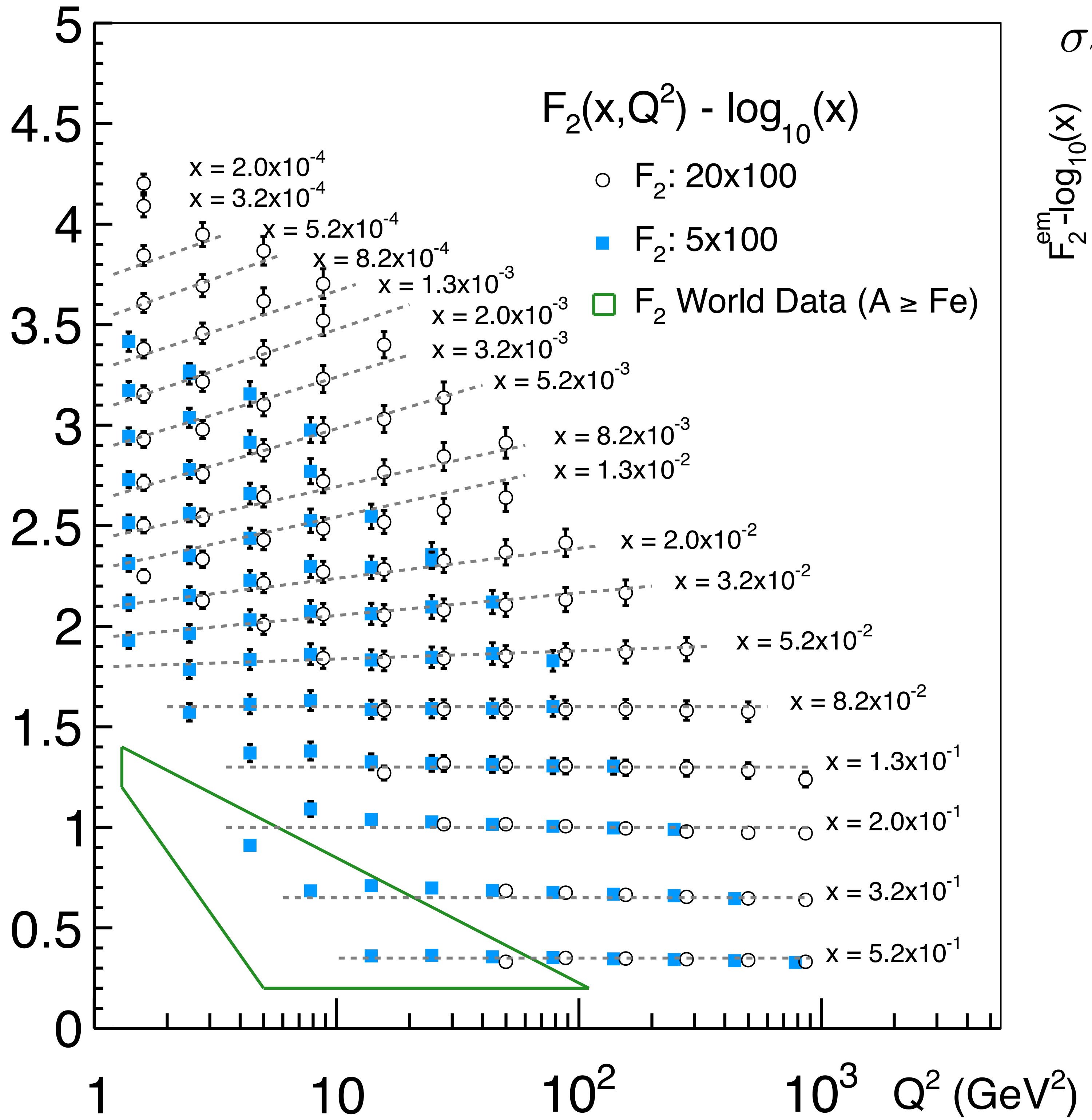

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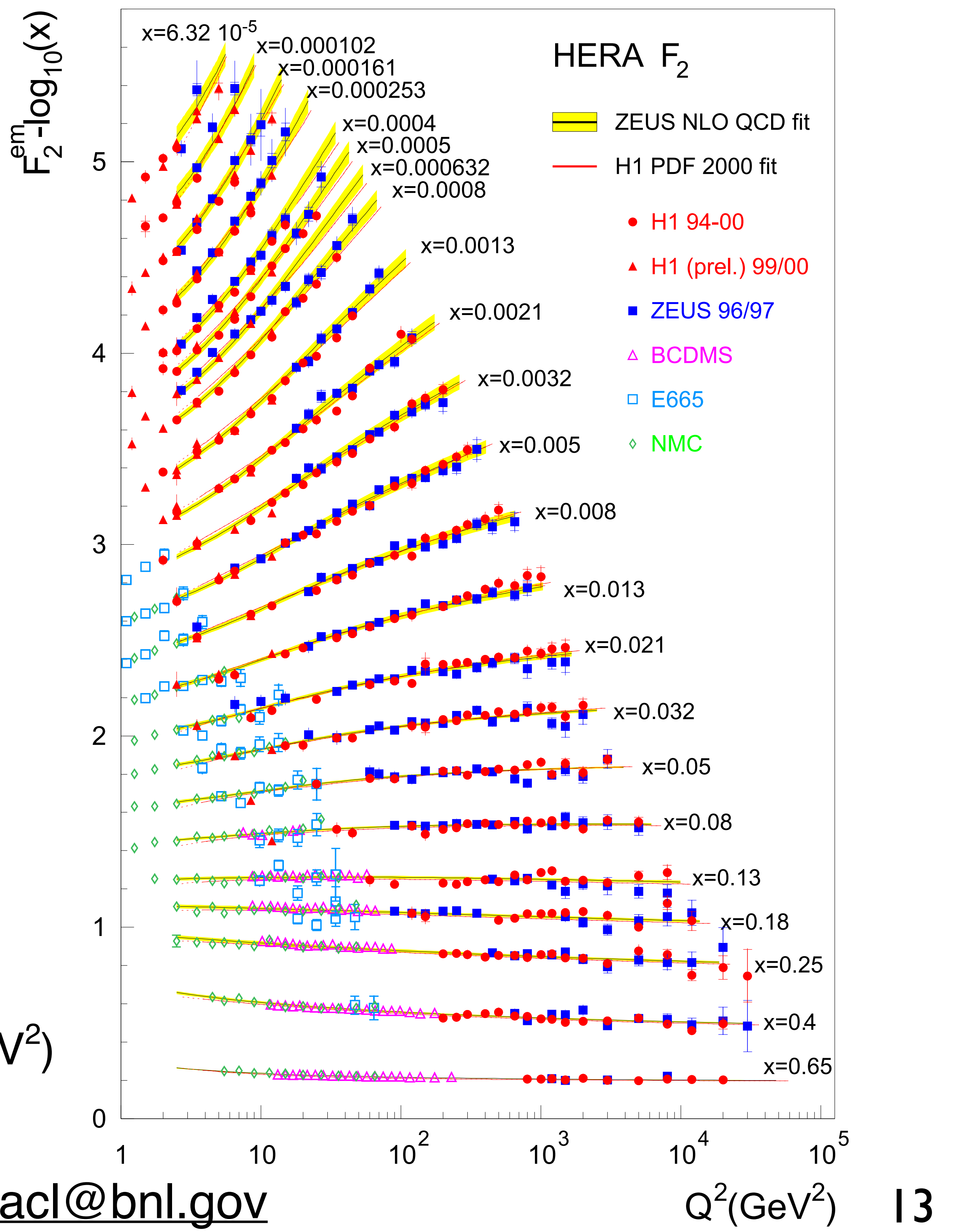

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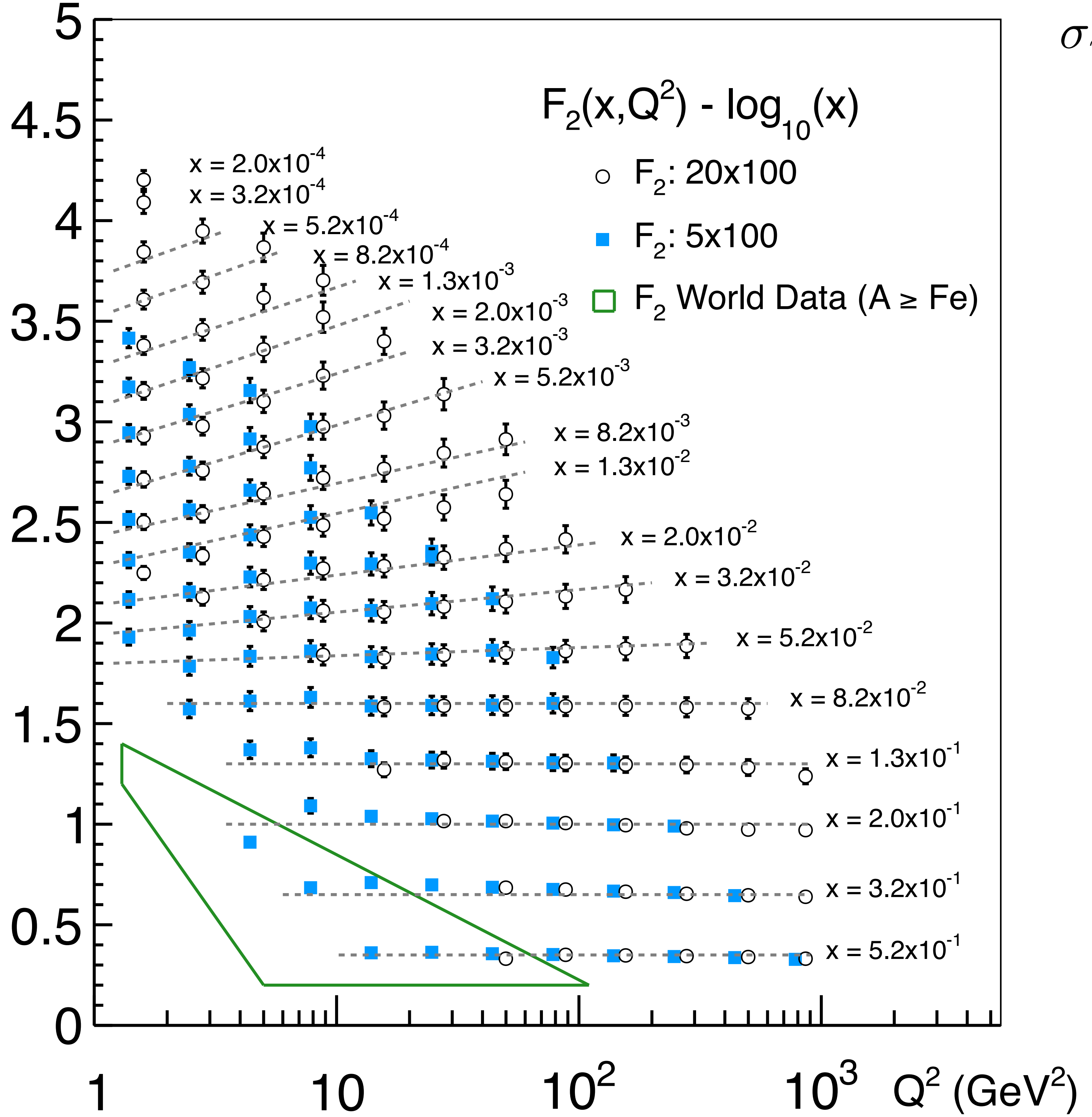


3% systematic errors added in quadrature

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+}F_L^A(x,Q^2)$$

- F_2^{Au} as a function of x and Q^2
- Same scaling employed as the HERA plot
- Scaling violation observed at low (x,Q^2)
  - ➡Need to go to higher energies to observe the scaling
    - Difficult to see with a staged approach to the machine
- Entering a new region of phase-space not previously explored in nuclei
- Dominated by systematic uncertainties

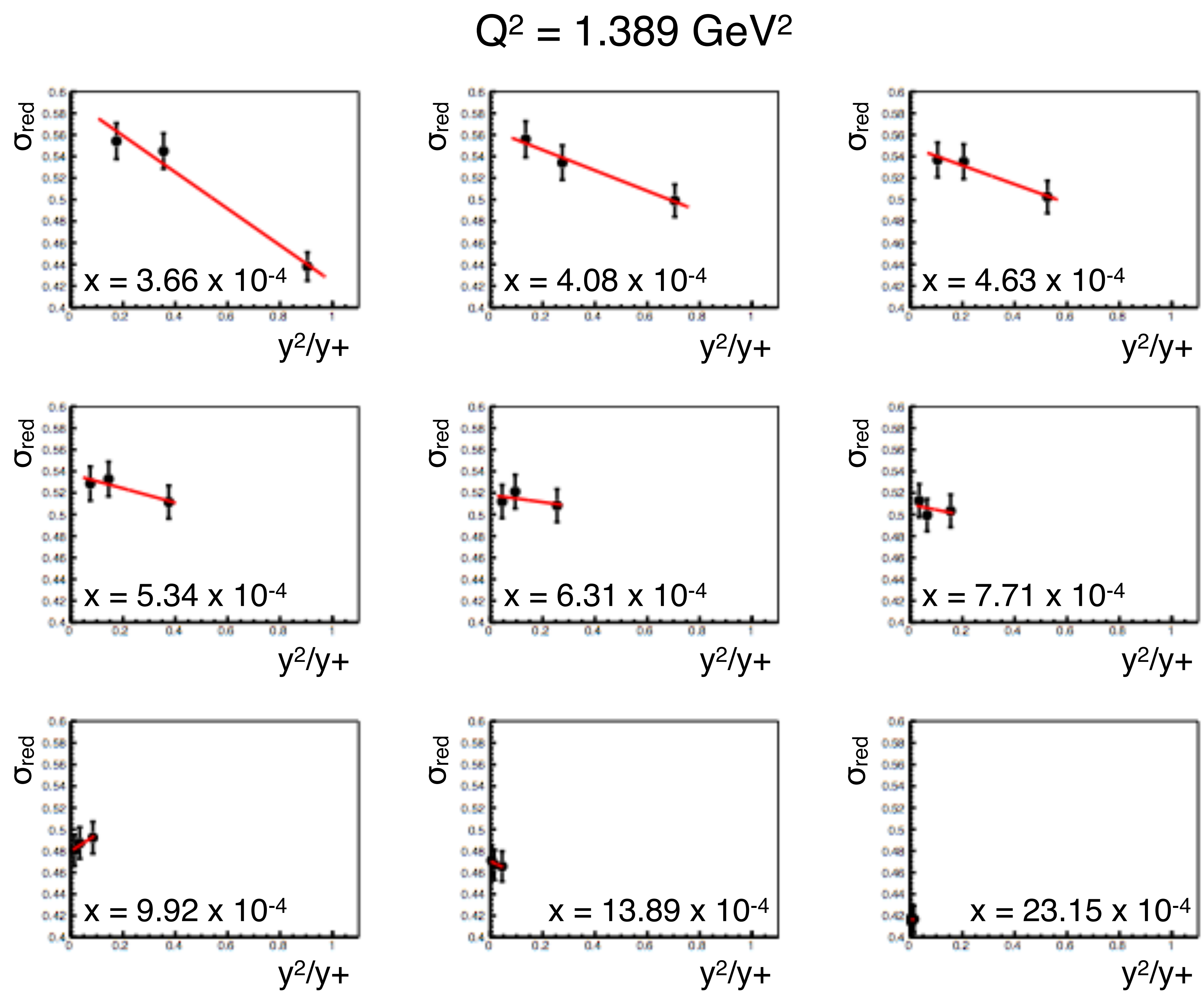
Feasibility study of F_L^A: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+}F_L^A(x,Q^2)$

Strategies:
slope of y^2/Y_+ for different s at fixed x & Q^2

e+Au:
20x50 - A∫Ldt = 2 fb^{-1}
20x75 - A∫Ldt = 4 fb^{-1}
20x100 - A∫Ldt = 4 fb^{-1}
running combined
~6 months total running (50% eff)

statistical errors are swamped by the 3% systematic errors

Will be dominated by systematics, but would need a full detector simulation in order to estimate them



Feasibility study of F_L^A: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+}F_L^A(x,Q^2)$

Strategies:
slope of y^2/Y_+ for different s at fixed x & Q^2

e+Au:
20x50 - $A\int Ldt$ = 2 fb^{-1}
20x75 - $A\int Ldt$ = 4 fb^{-1}
20x100 - $A\int Ldt$ = 4 fb^{-1}
running combined
~6 months total running (50% eff)

statistical errors are swamped by the 3% systematic errors

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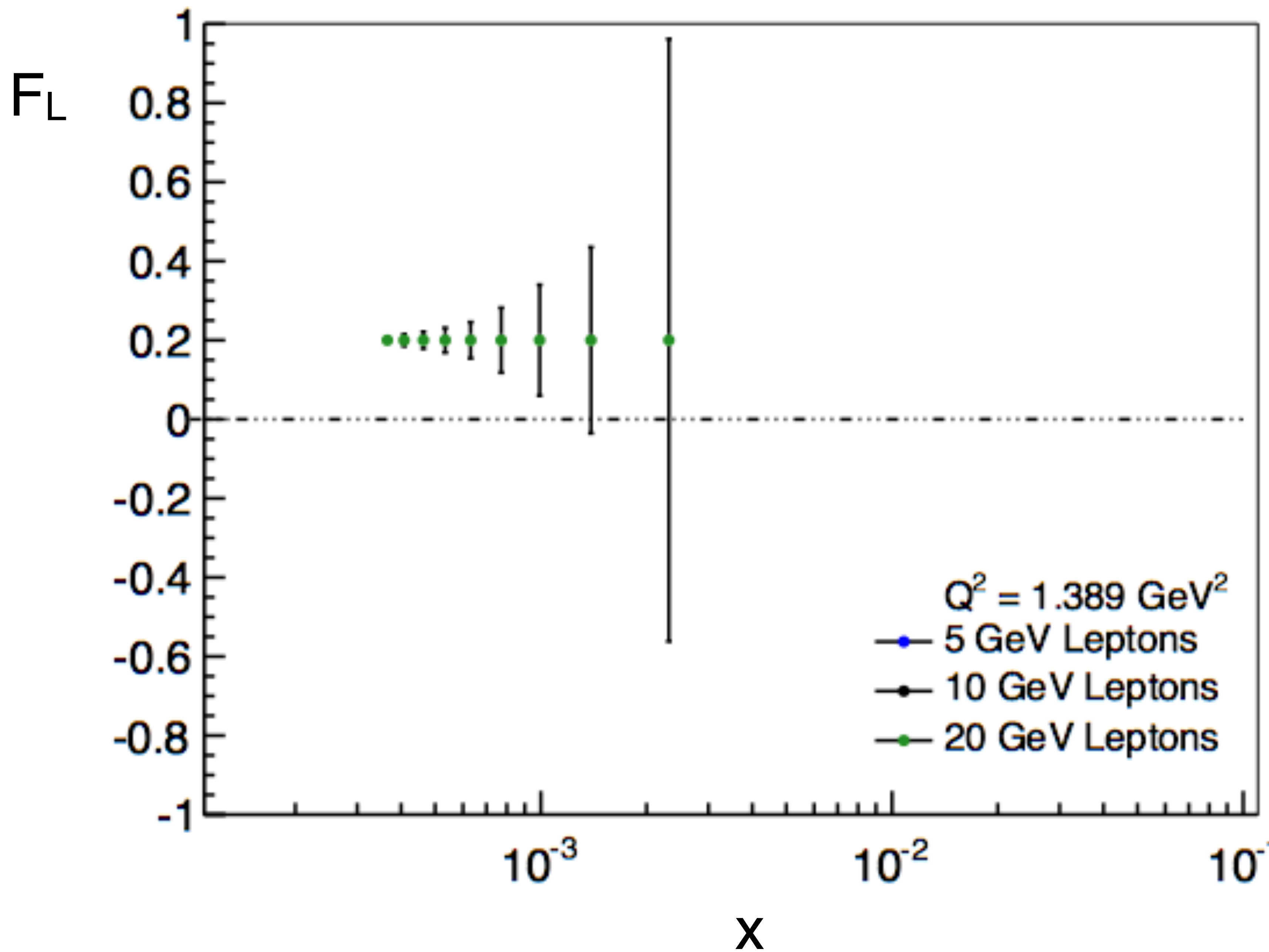

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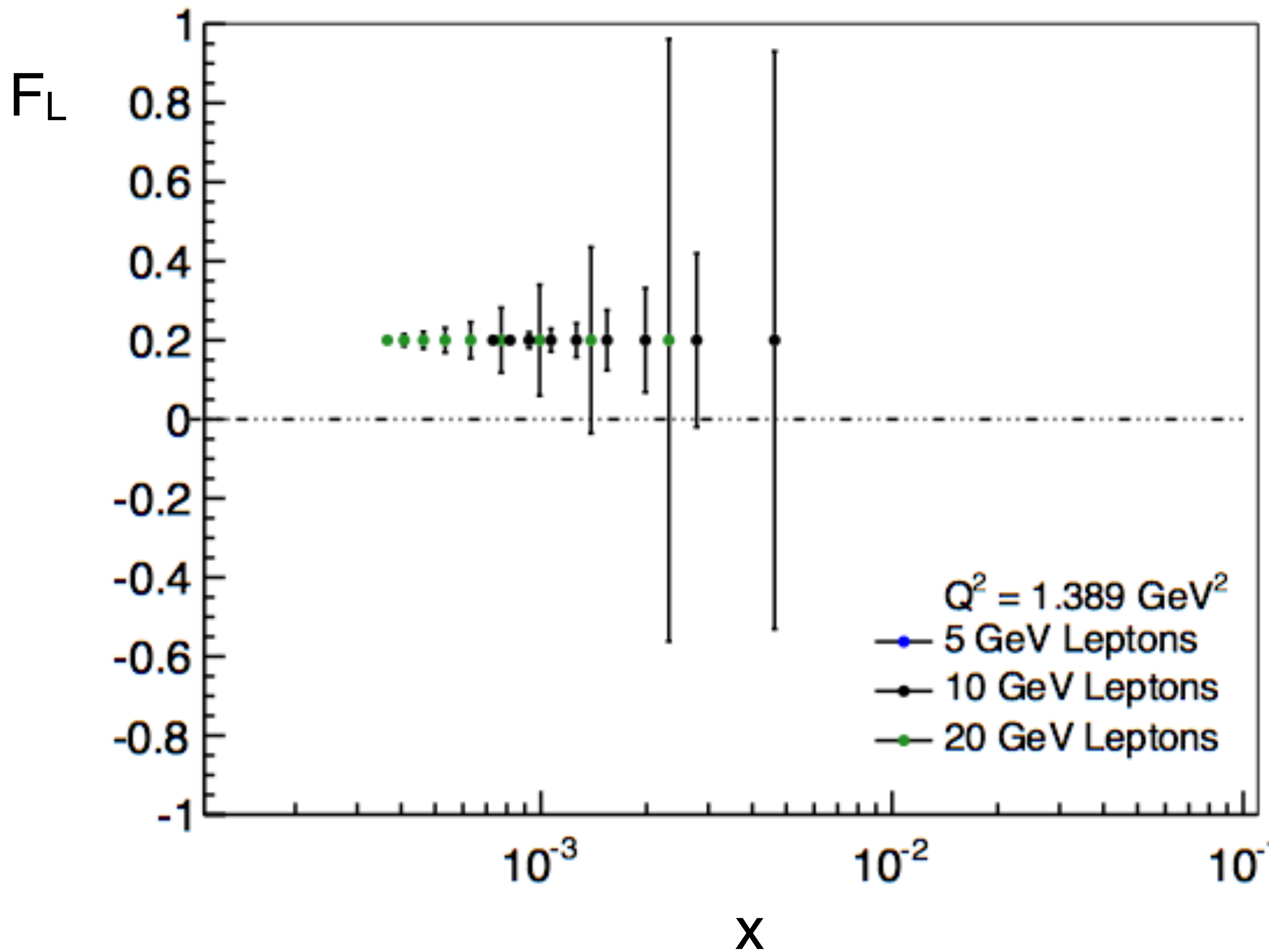

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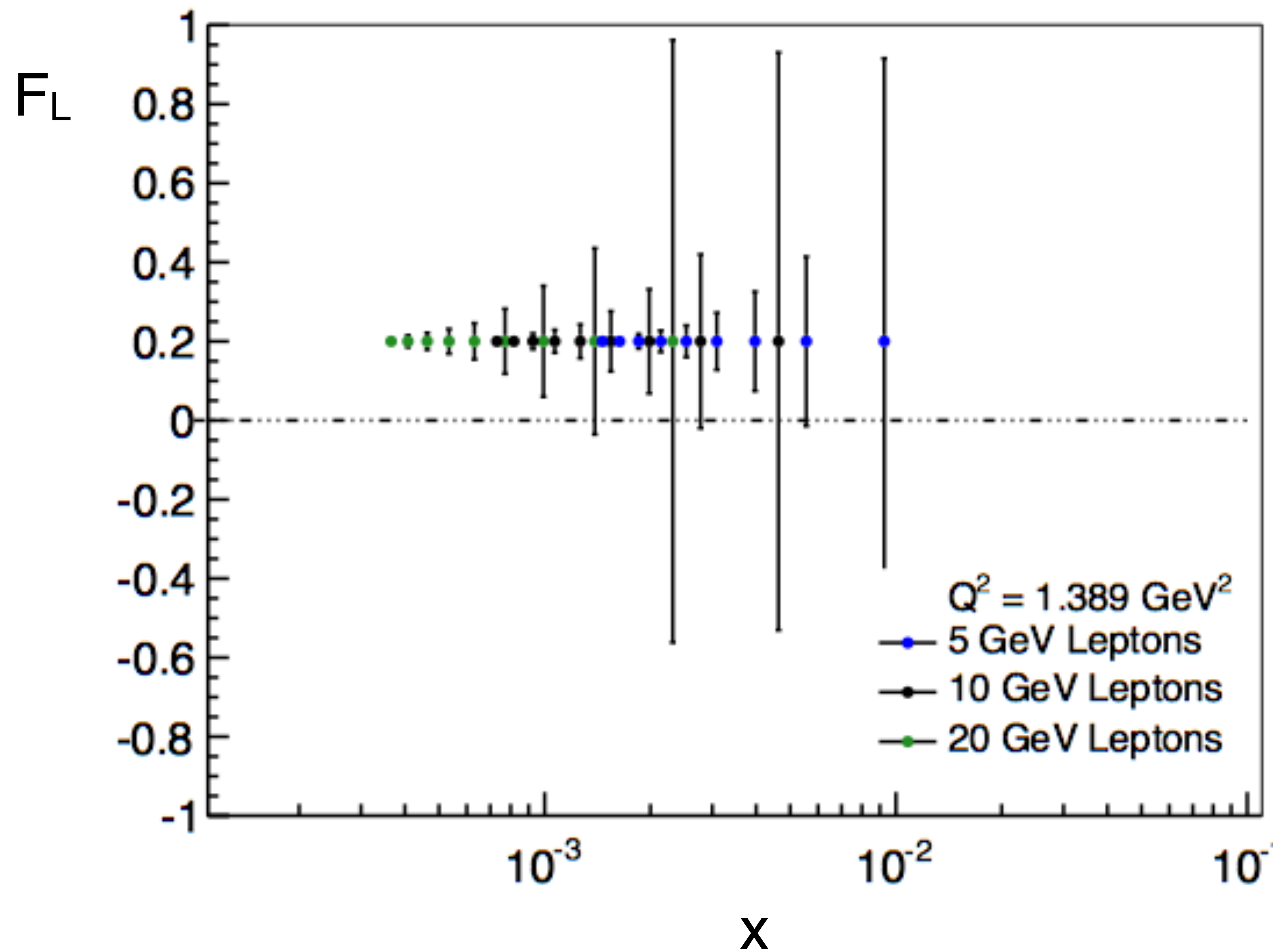

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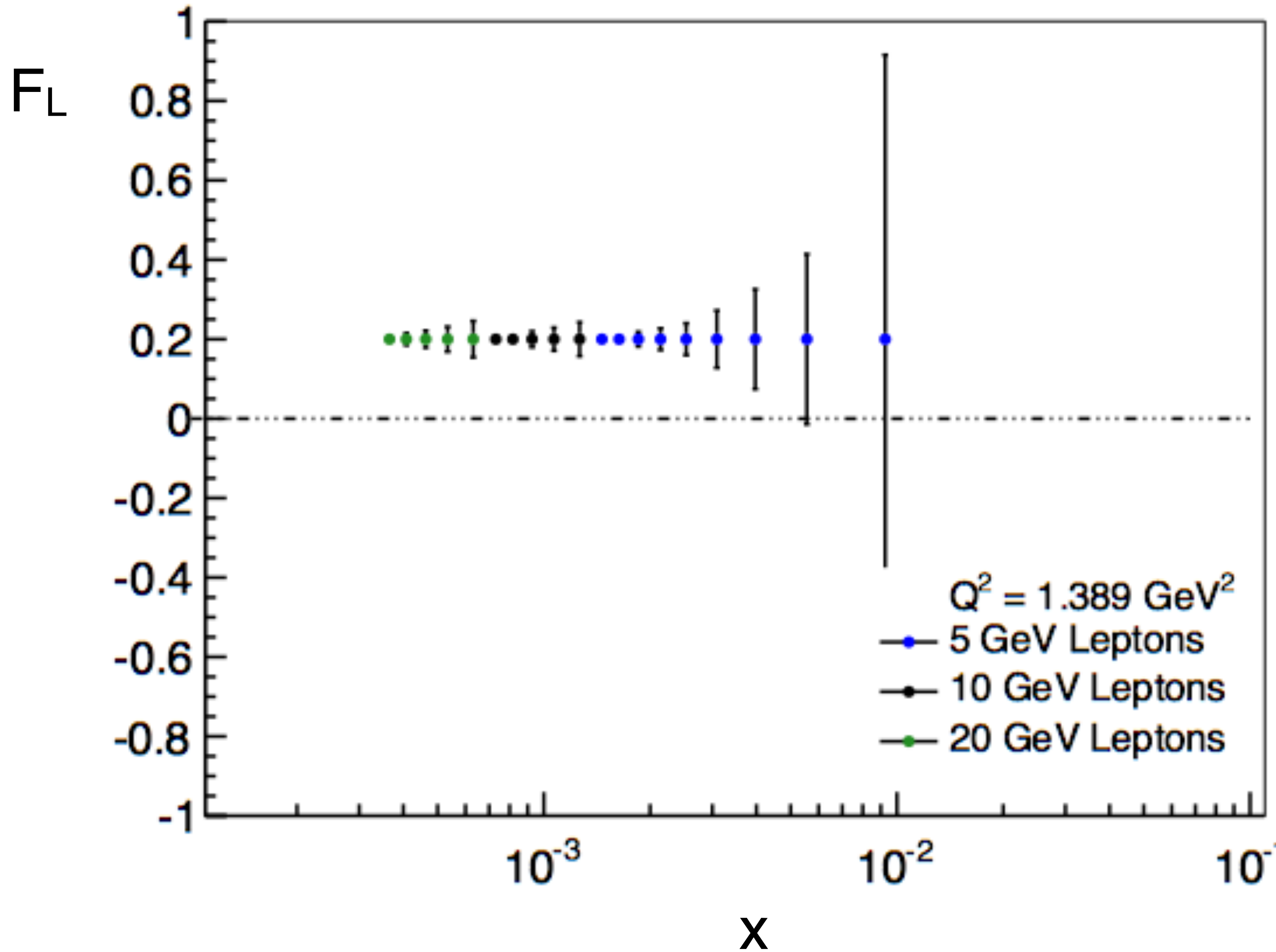
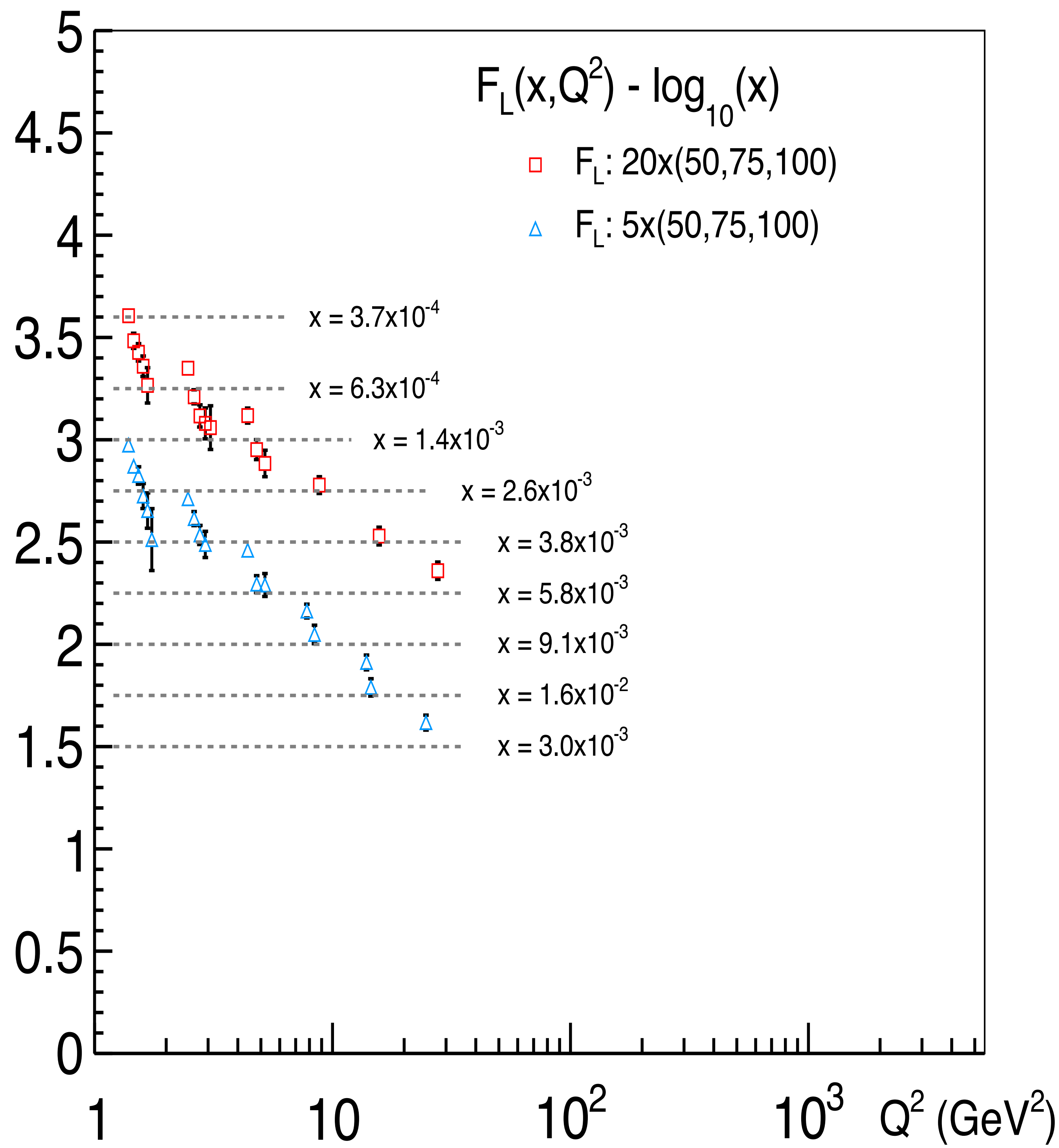


A precision measurement of the F_L^A nuclear structure function



3% systematic errors added in quadrature

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y+} F_L^A(x, Q^2)$$

- F_L^{Au} as a function of x and Q^2
- Same scaling employed as the HERA plot
- Much smaller coverage in Scaling violation observed at low (x,Q^2) than F_2^{Au} as expected

  ➡ Requires same (x,Q^2) coverage at 3 different energies

- Phase space increased by having as many energies as possible

Comparison to theory: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+} F_L^A(x,Q^2)$

Strategies:
slope of y^2/Y_+ for different s at fixed x & Q^2

e+Au: 1st stage
5x50 - A∫Ldt = 2 fb^{-1}
5x75 - A∫Ldt = 4 fb^{-1}
5x100 - A∫Ldt = 4 fb^{-1}
running combined
~6 months total running (50% eff)

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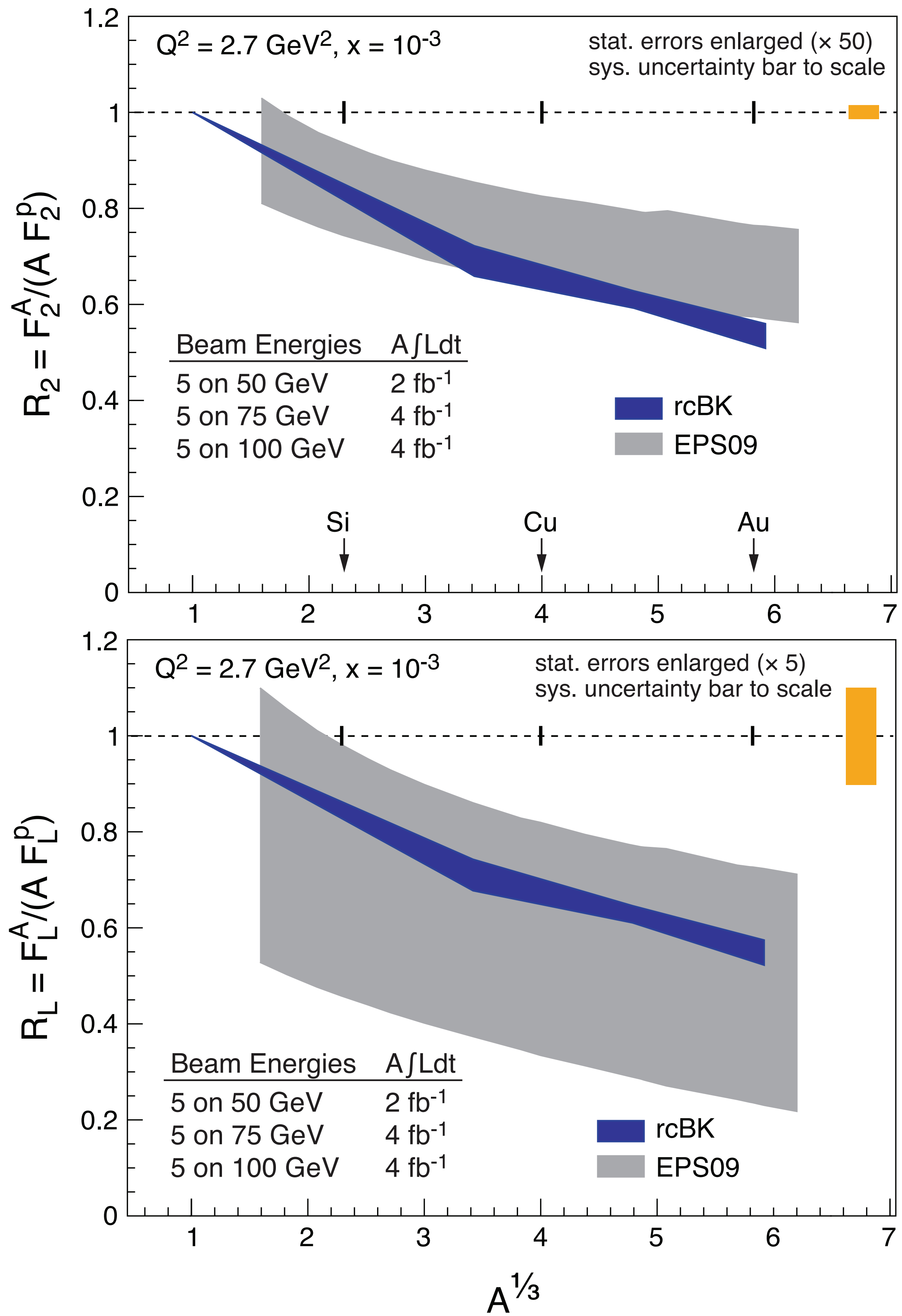

Work in progress… (H. Paukkunen)

- Take the generated Pseudo-data and include it in a global fit

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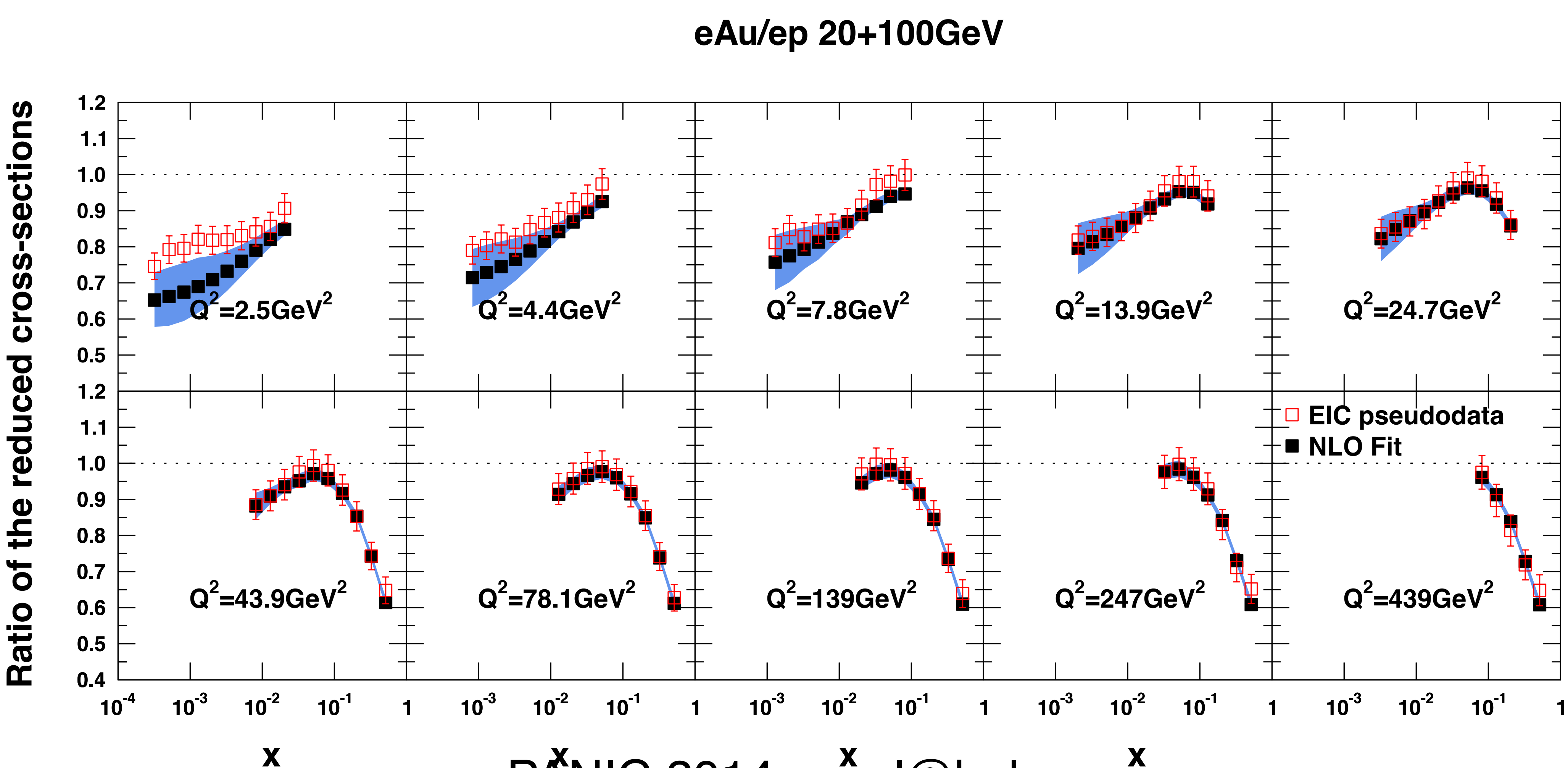

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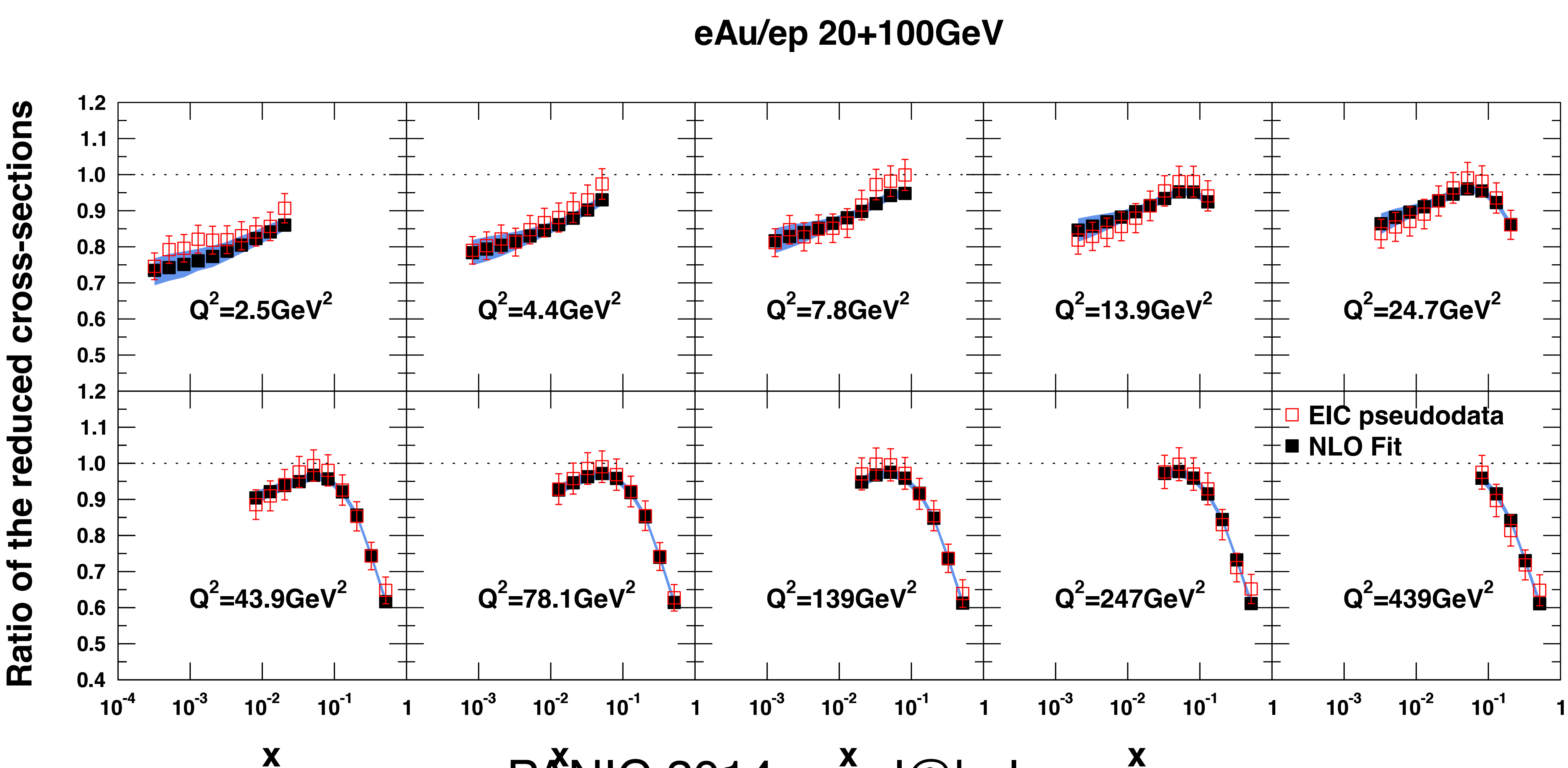

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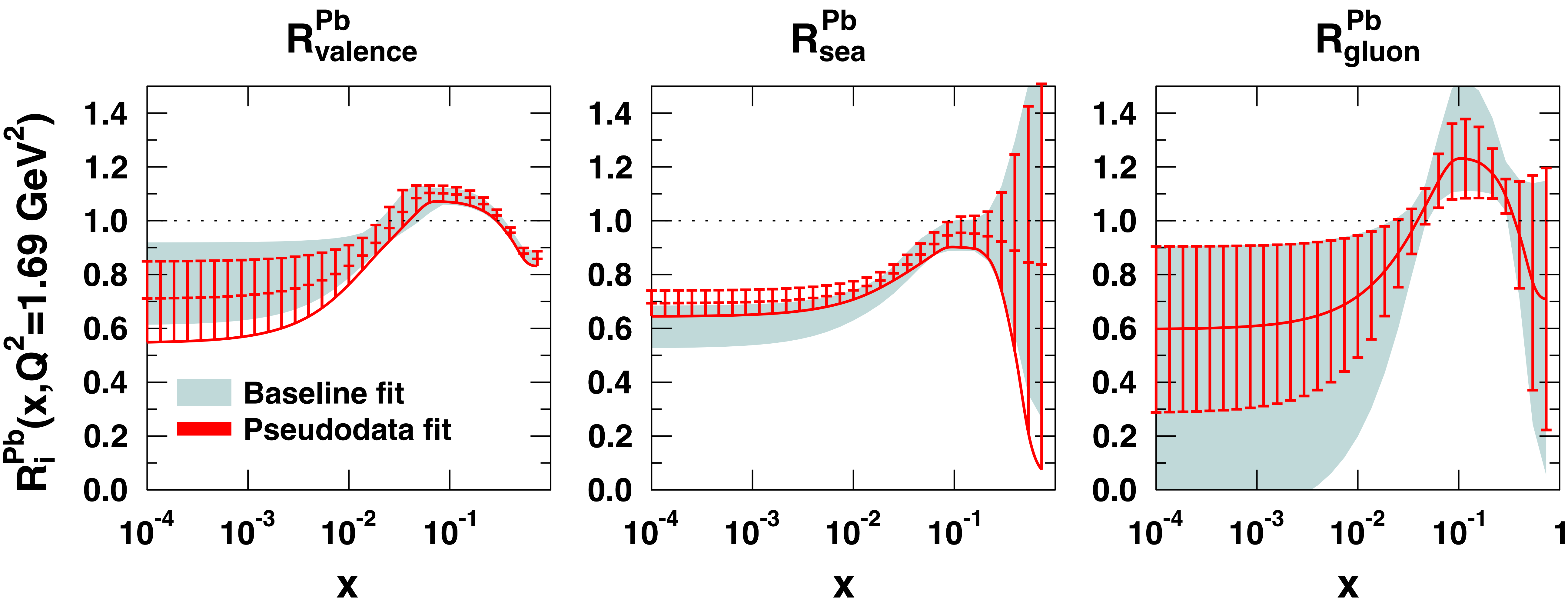
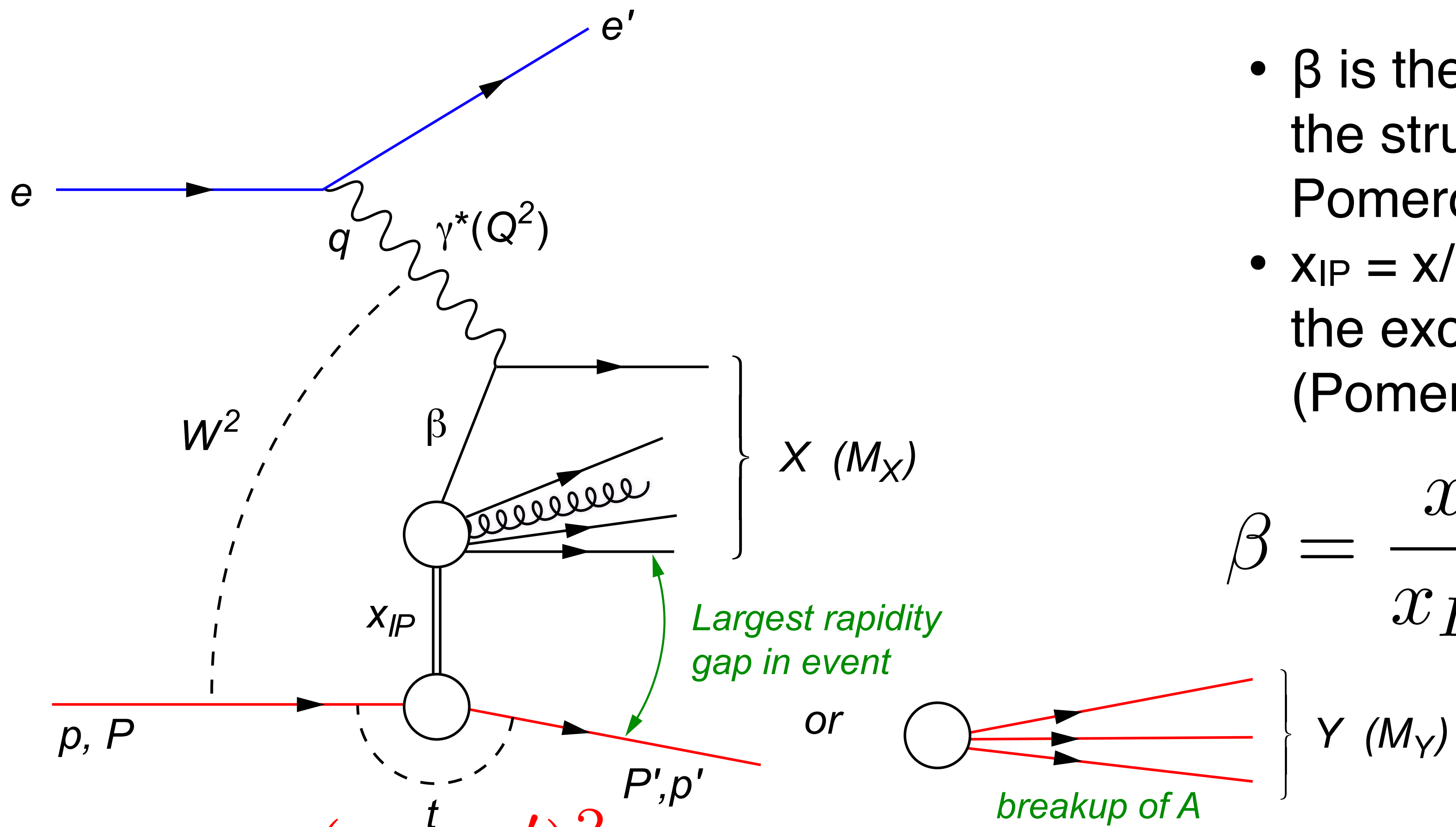


Exclusive processes in e+A - diffraction



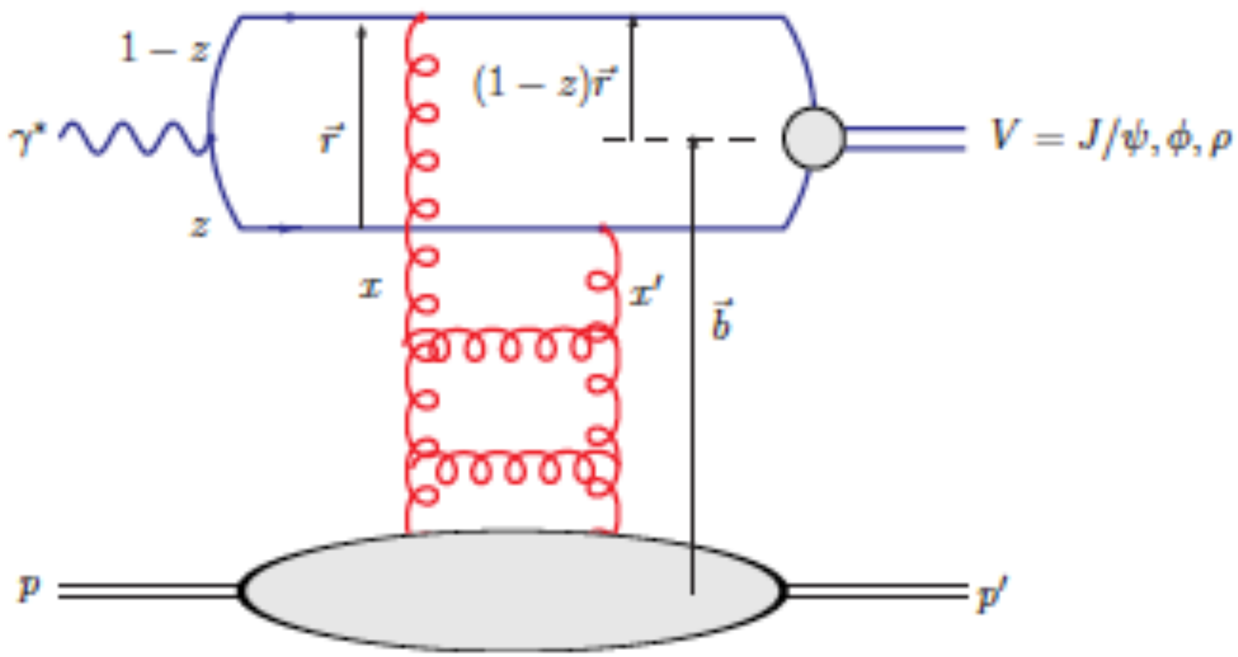
$$t = (p - p')^2$$

- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

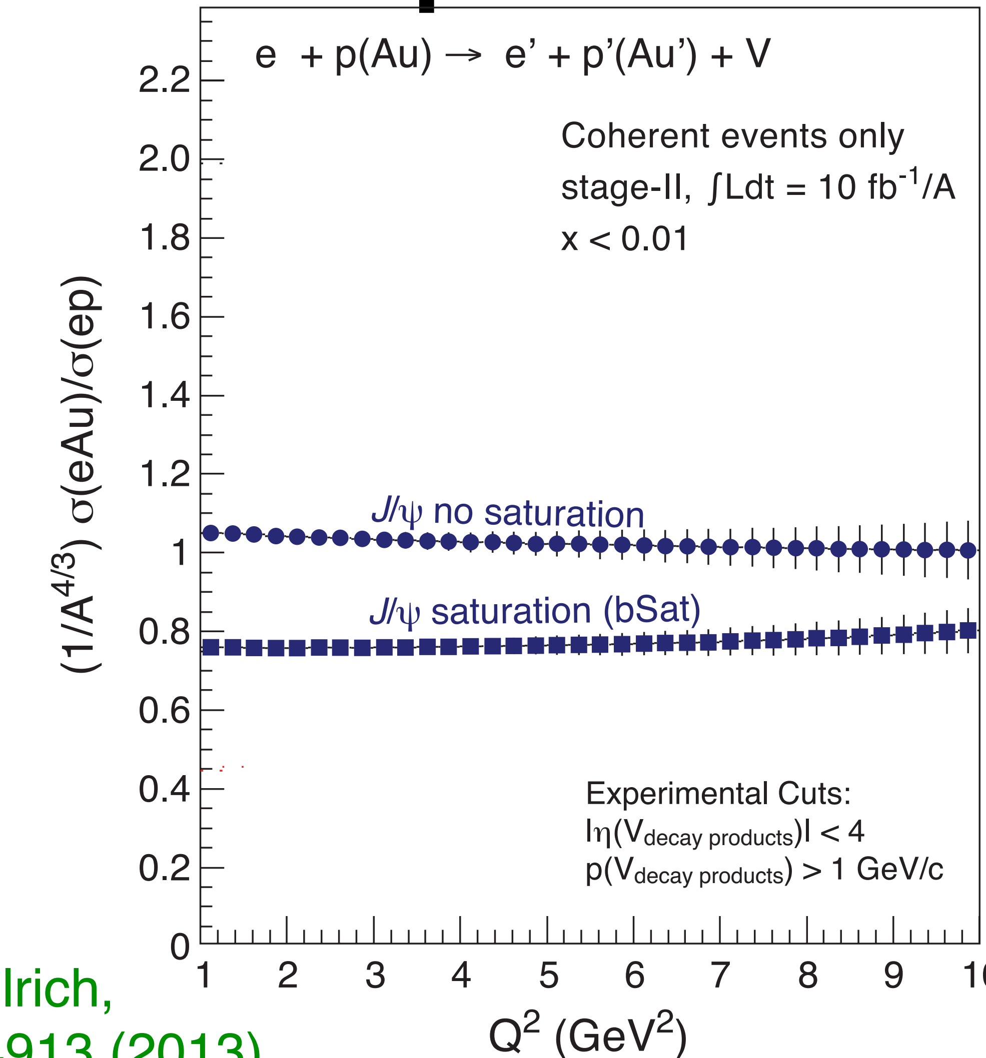
$$\beta = \frac{x}{x_{I\!P}} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

- **Diffraction in e+p:**
  - ➡ HERA: 15% of all events are diffractive
- **Diffraction in e+A:**
  - ➡ Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%
  - ➡ Coherent diffraction (nuclei intact)
  - ➡ Incoherent diffraction: breakup into nucleons (nucleons intact)

Exclusive vector meson production



$$d\sigma \propto g(x)^2$$



Sartre: Toll, Ullrich,
Phys.Rev. C87, 024913 (2013)

- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation

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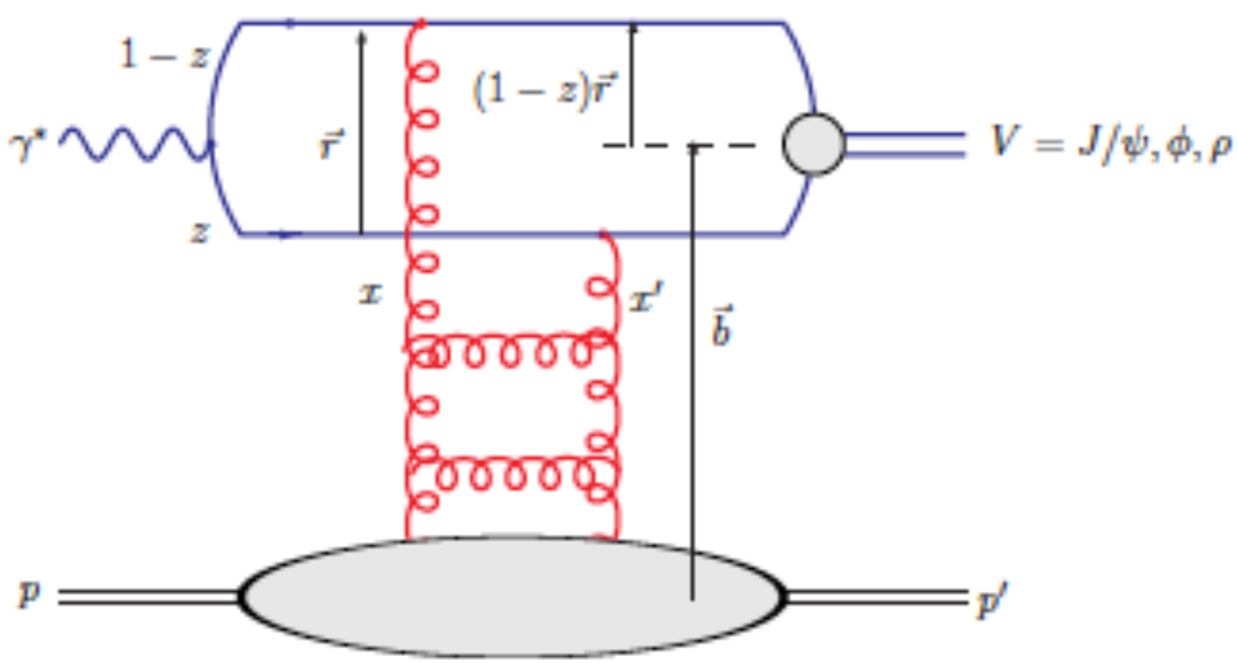

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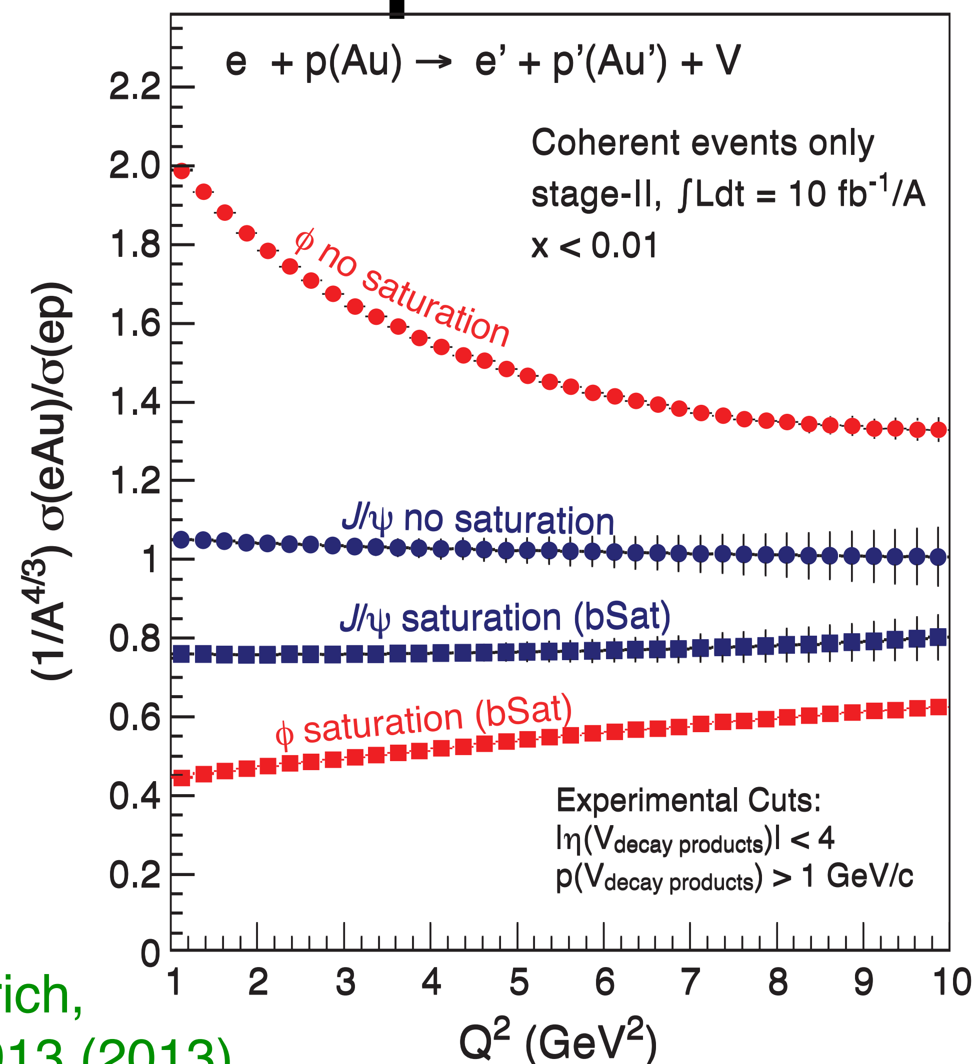
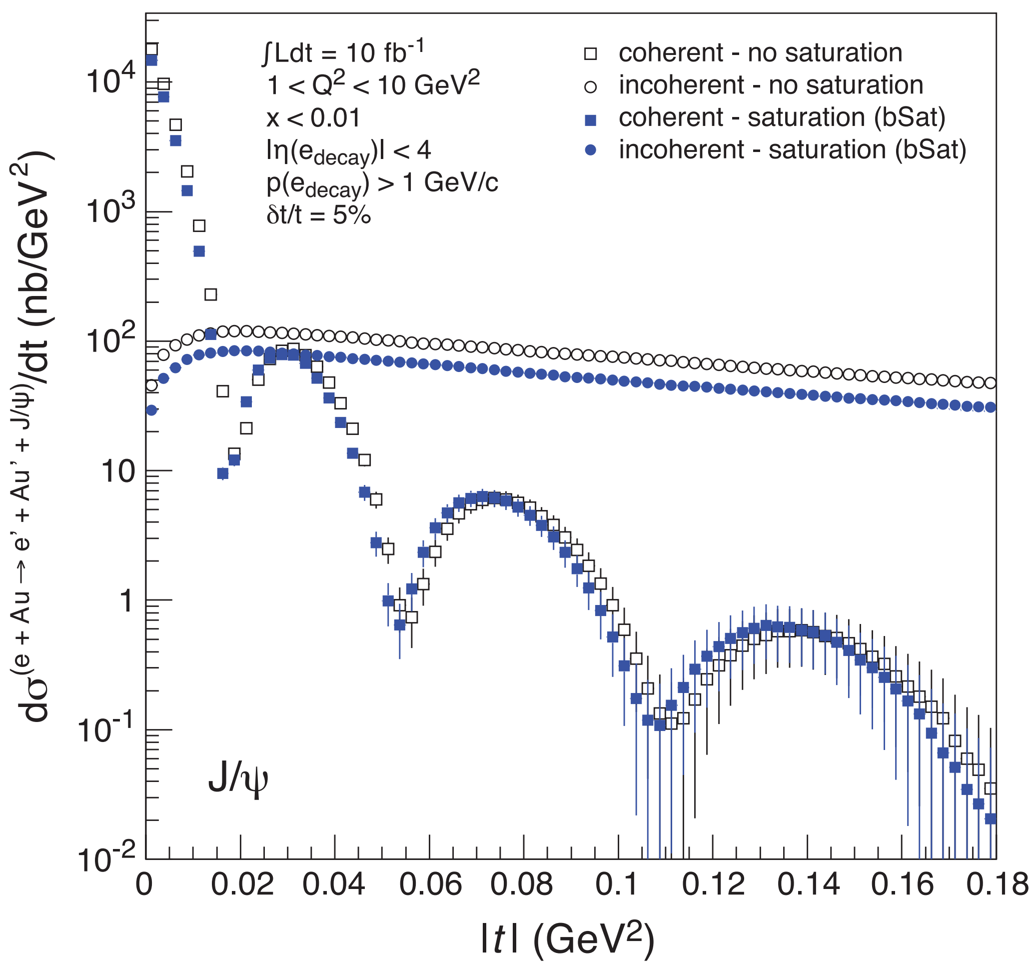
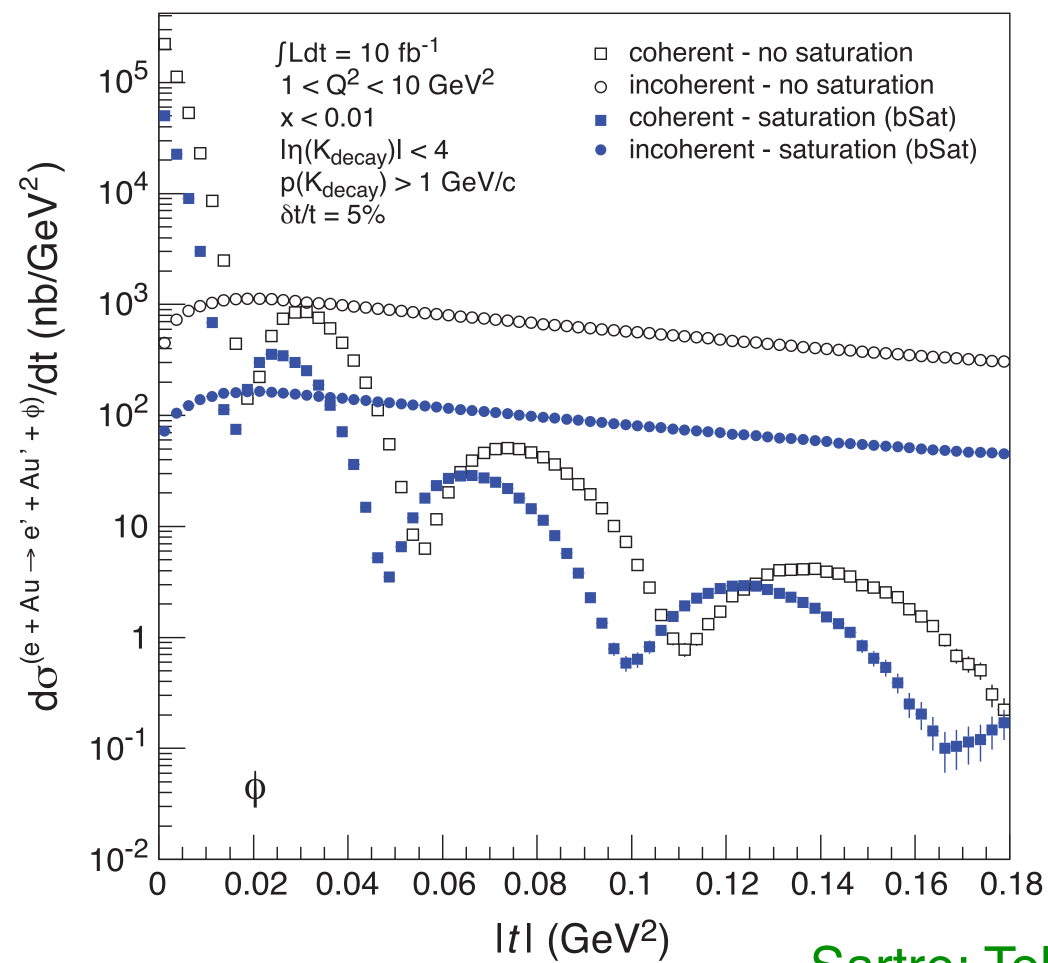


Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation
- φ shows a much larger difference
  - ➡wave function for φ is larger and hence more sensitive to saturation effects

Exclusive Vector Meson Production in e+A





Sartre: Toll, Ullrich, Phys.Rev. C87, 024913 (2013)

- Low-t: coherent diffraction dominates - gluon density
- High-t: incoherent diffraction dominates - gluon correlations

➡Need good breakup detection efficiency to discriminate between the two scenarios

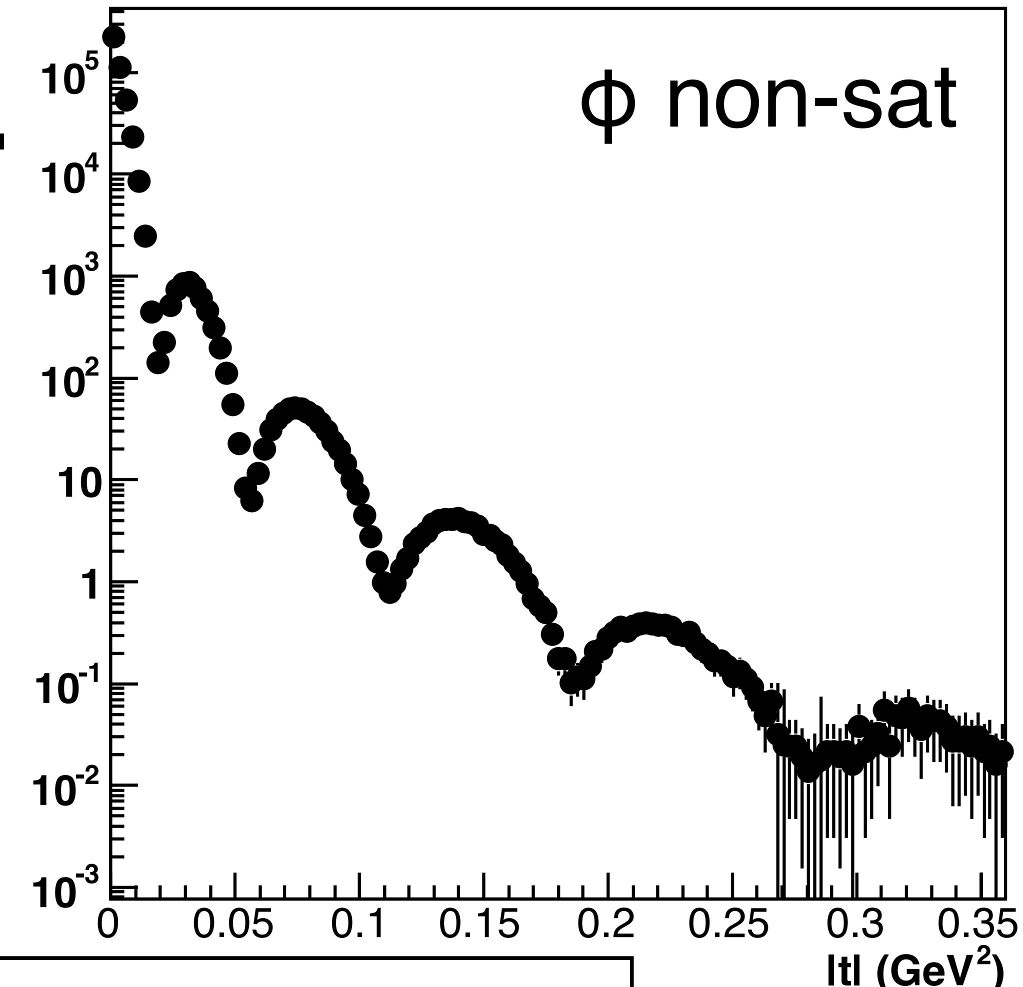
- unlike protons, forward spectrometer won't work for heavy ions
  - measure emitted neutrons in a ZDC
- rapidity gap with absence of break-up fragments sufficient to identify coherent events

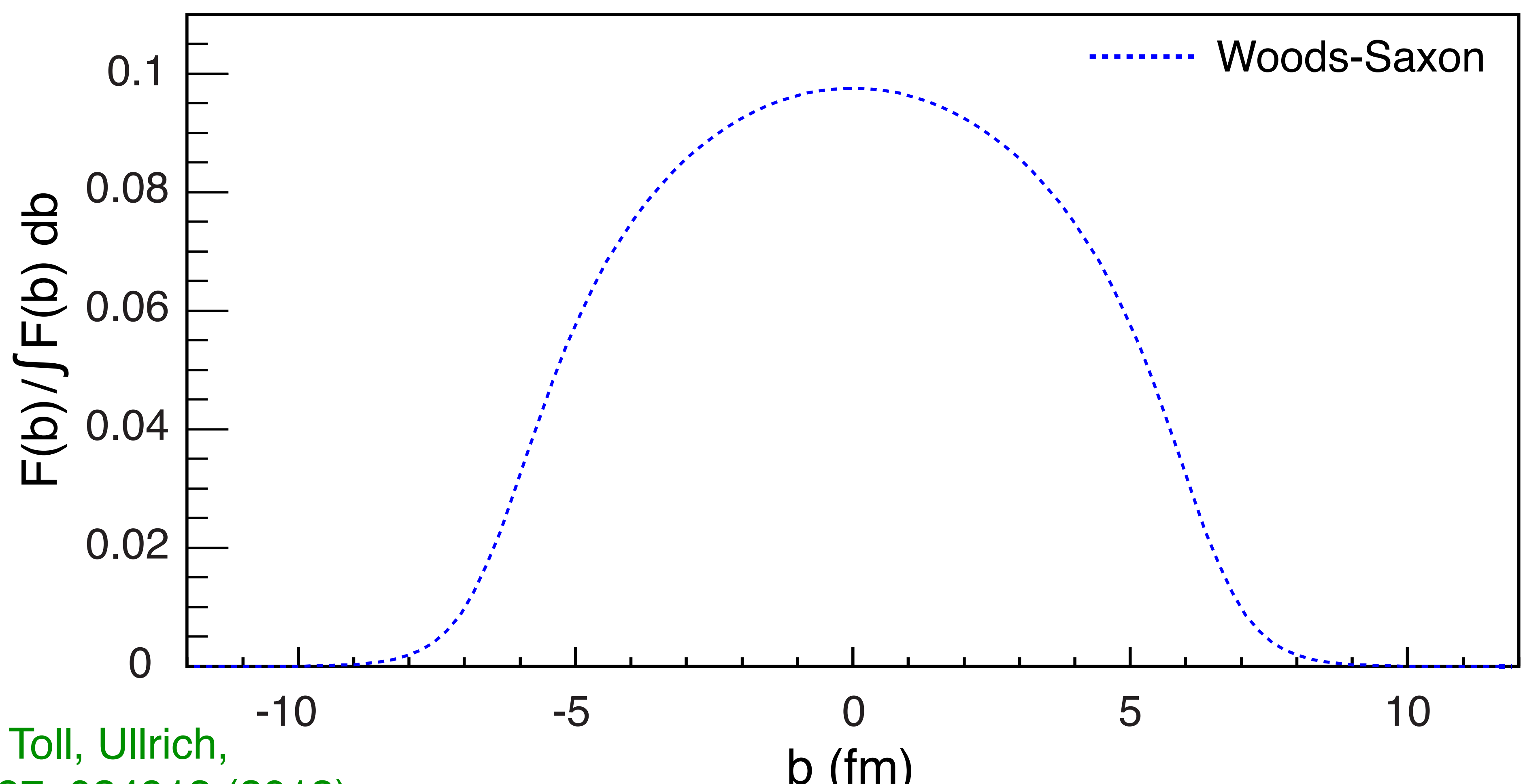
Finding the source...

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons

$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

$t = \Delta^2/(1-x) \approx \Delta^2$ (for small x)





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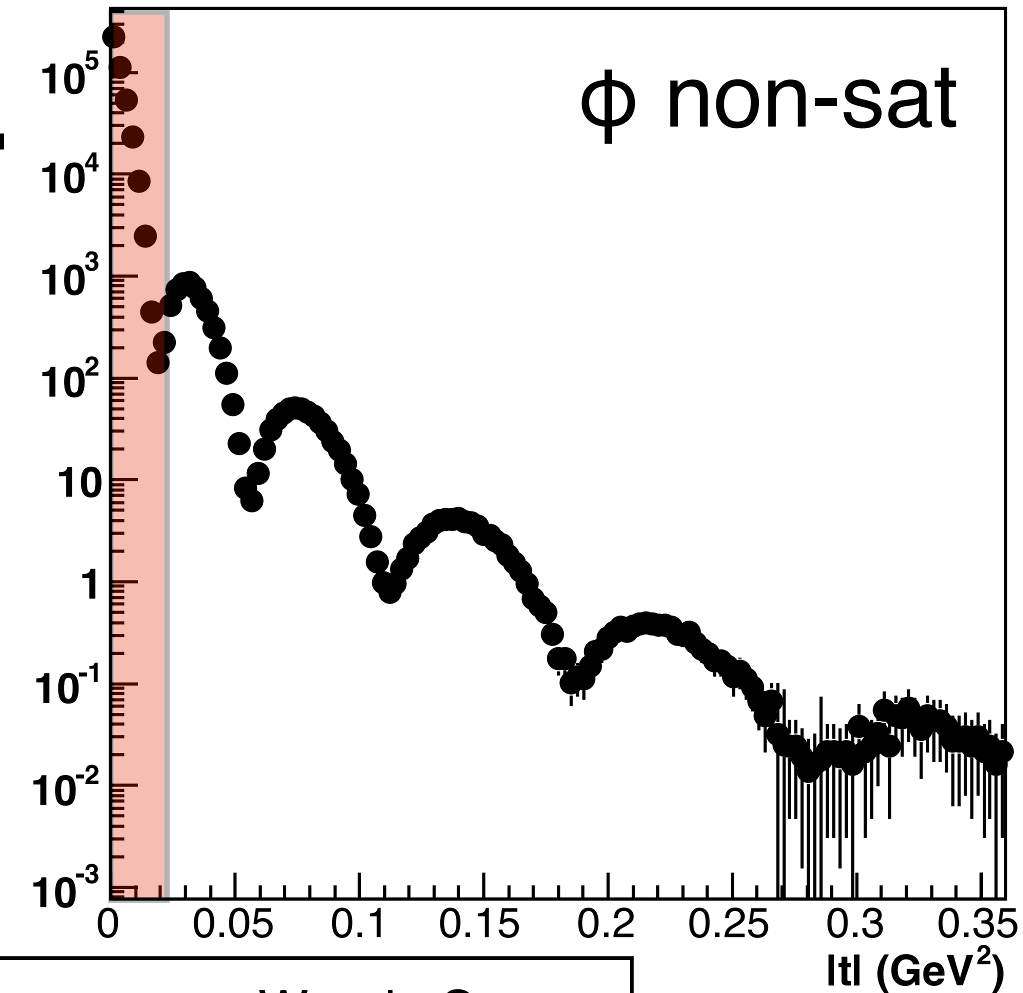

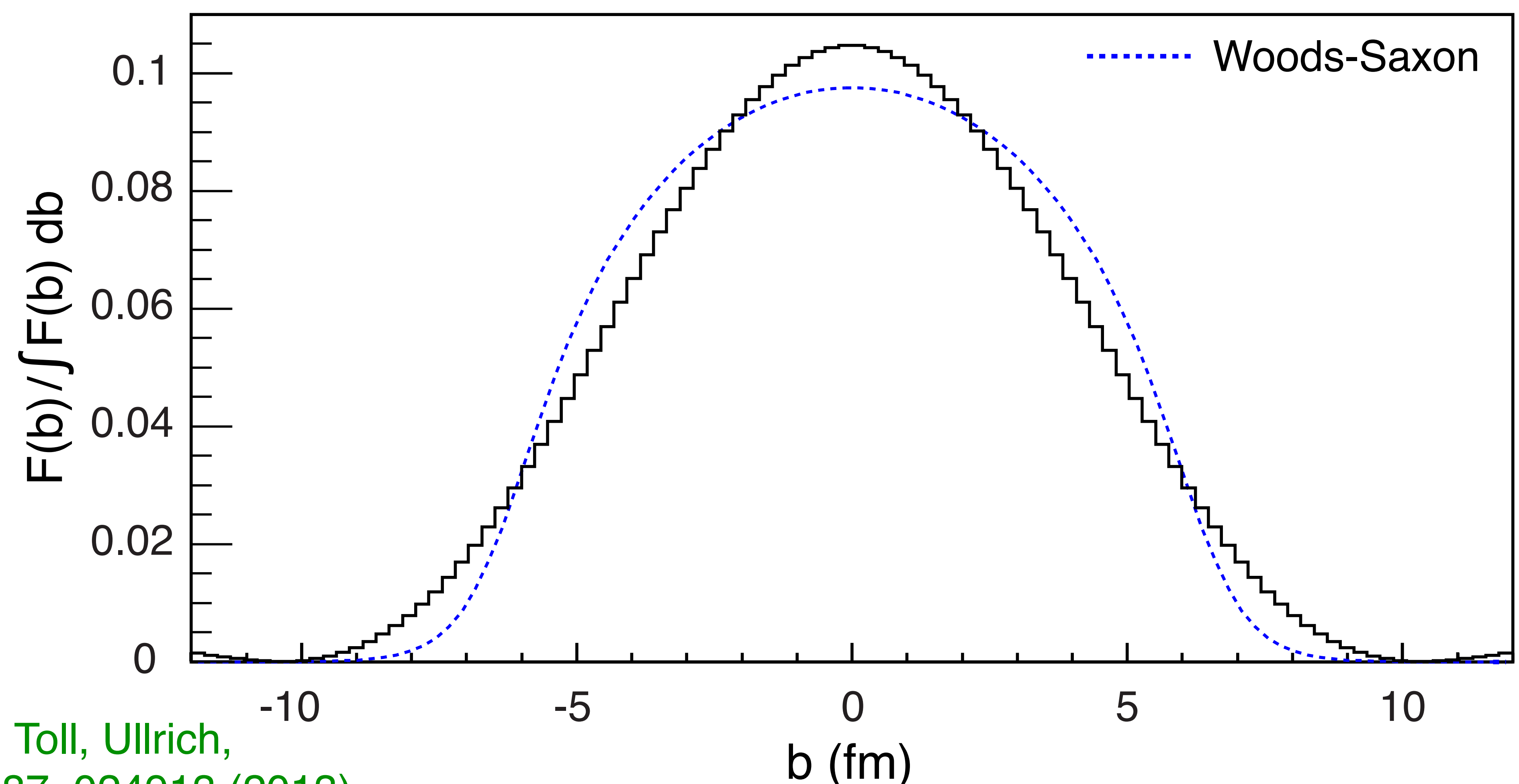

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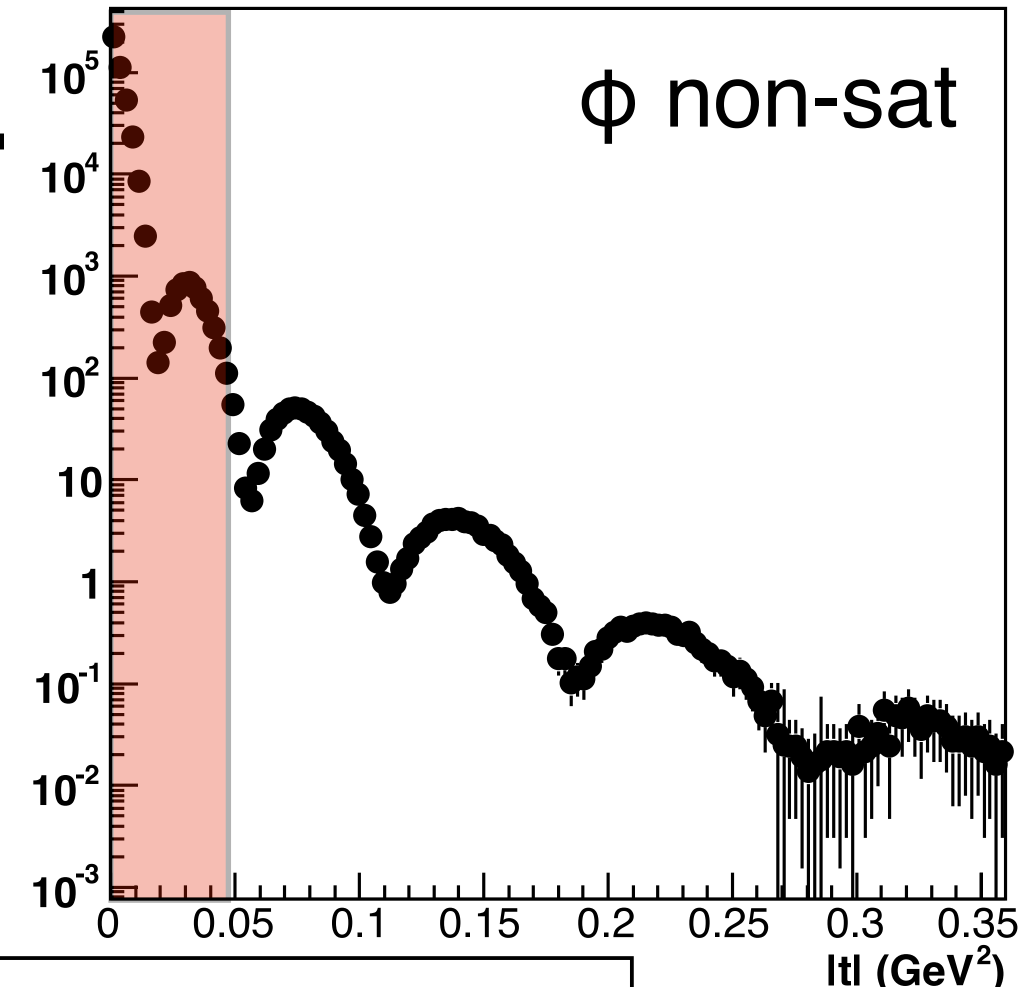

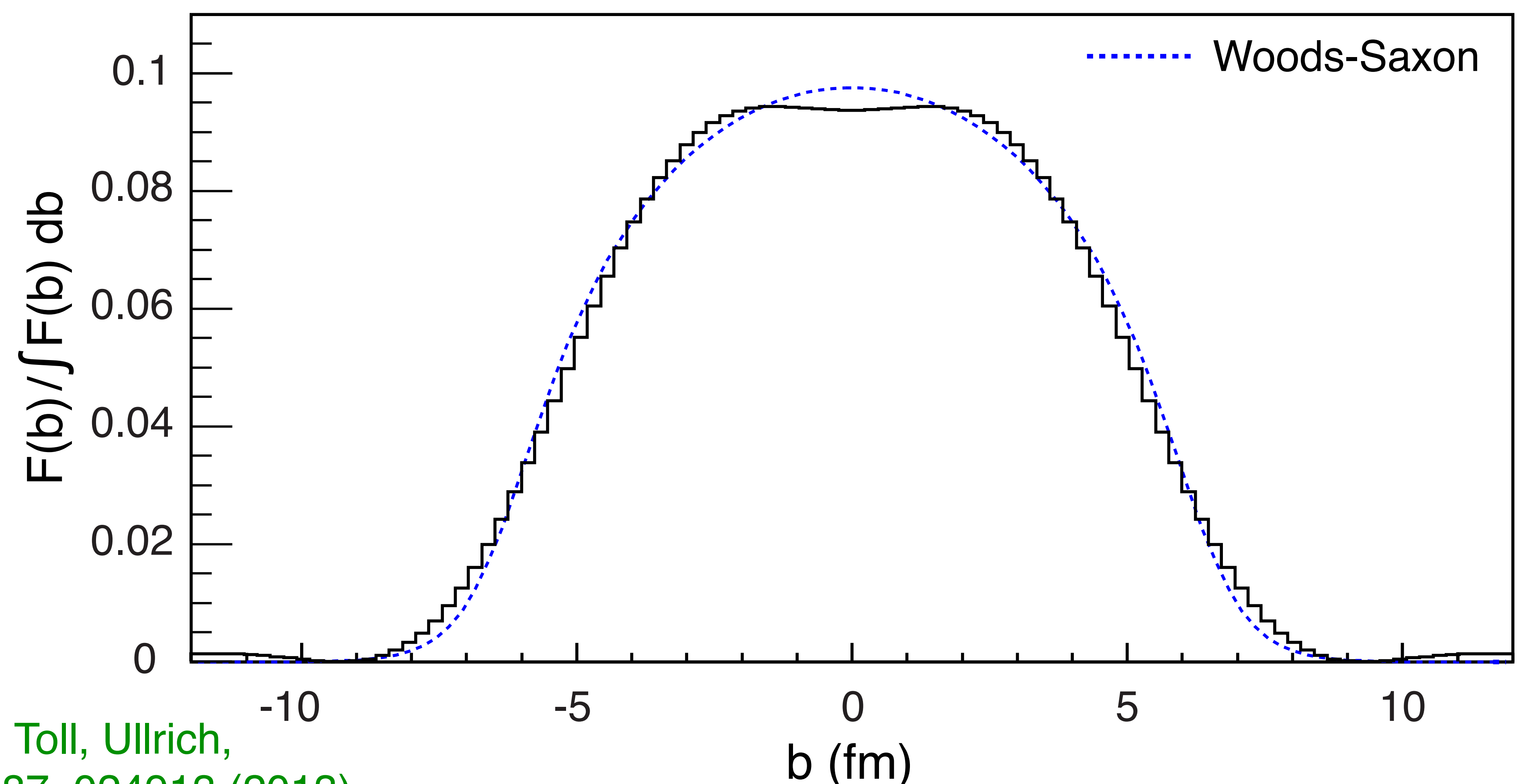

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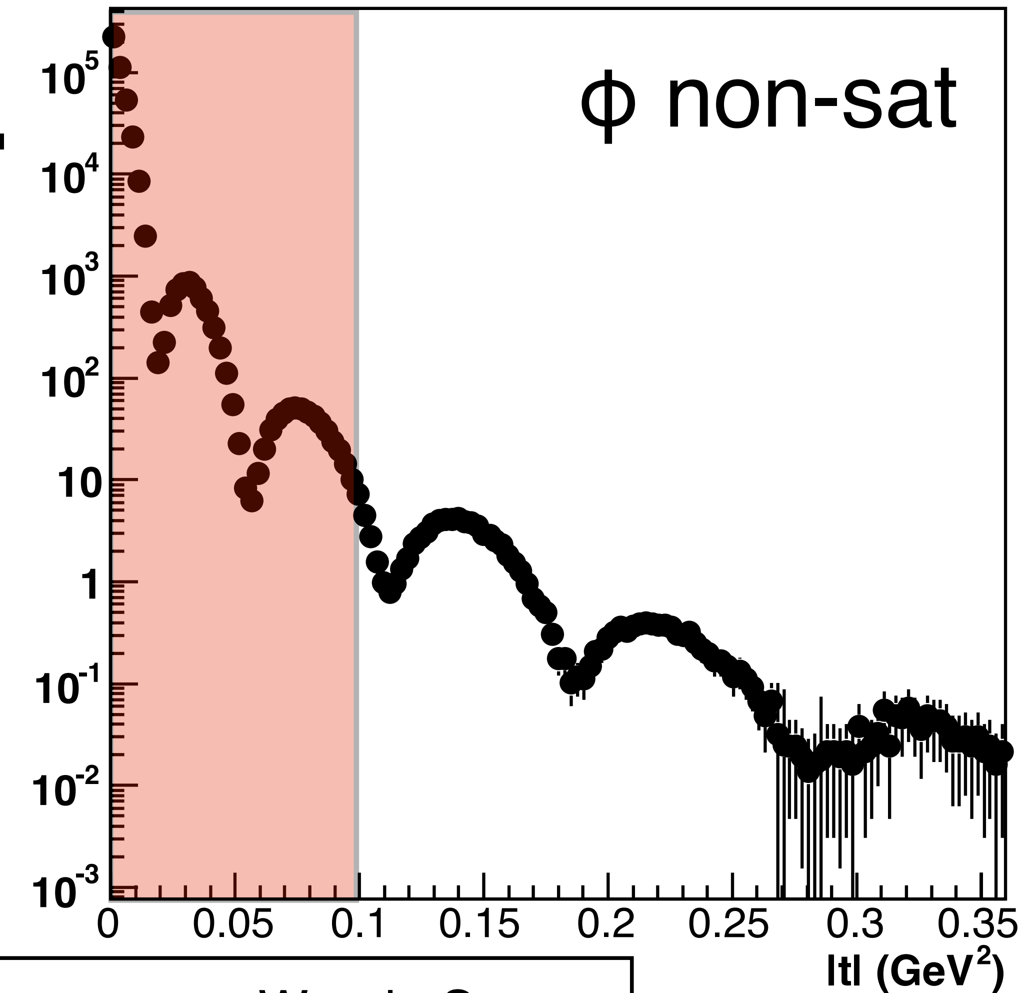

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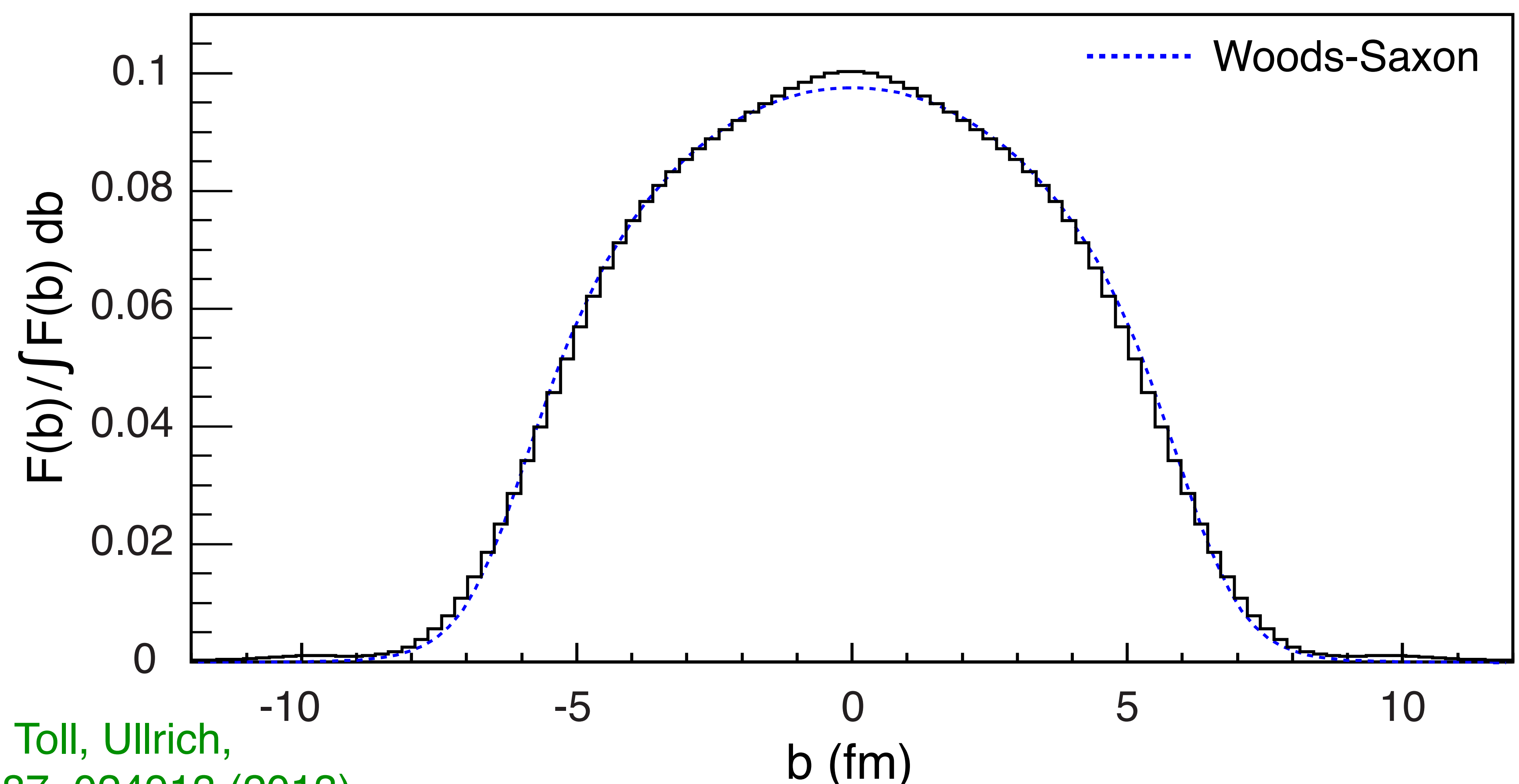

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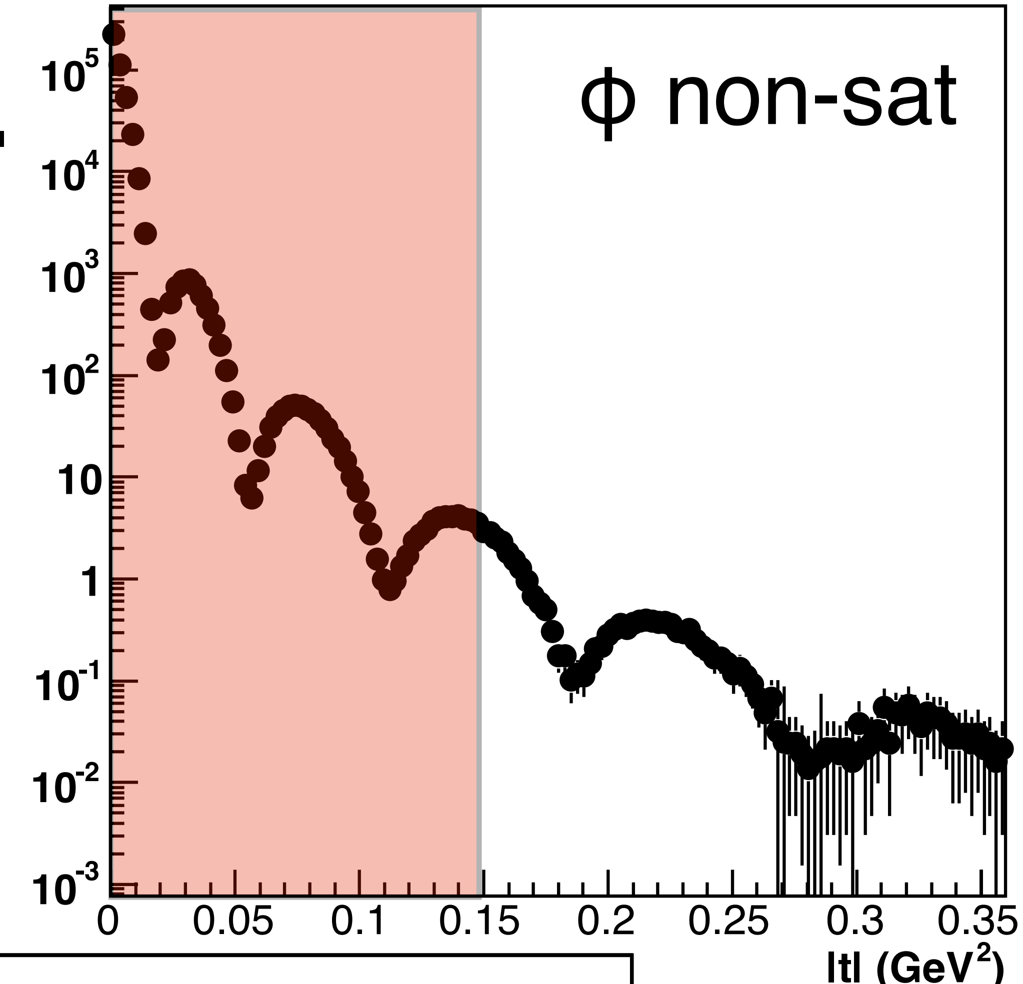

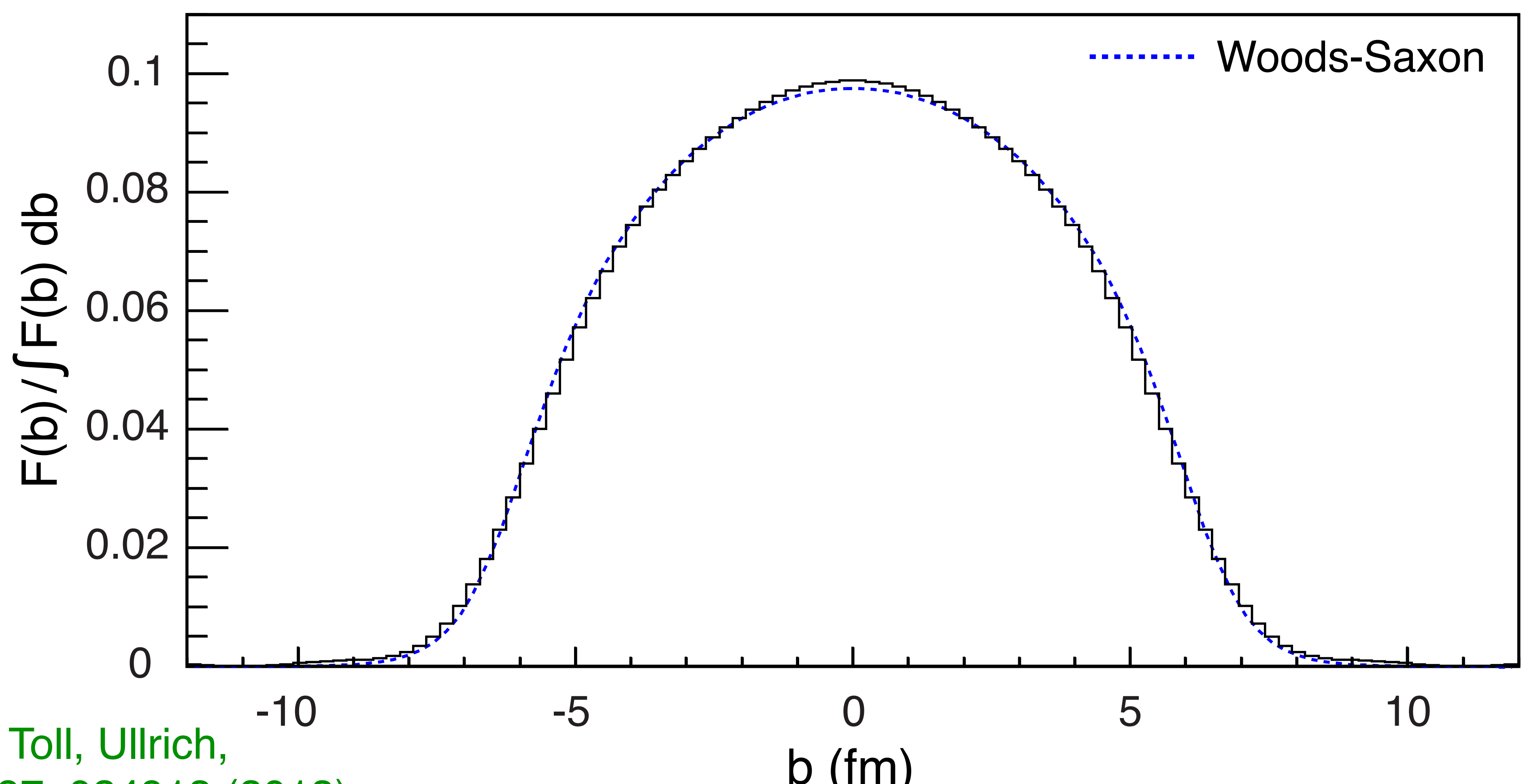

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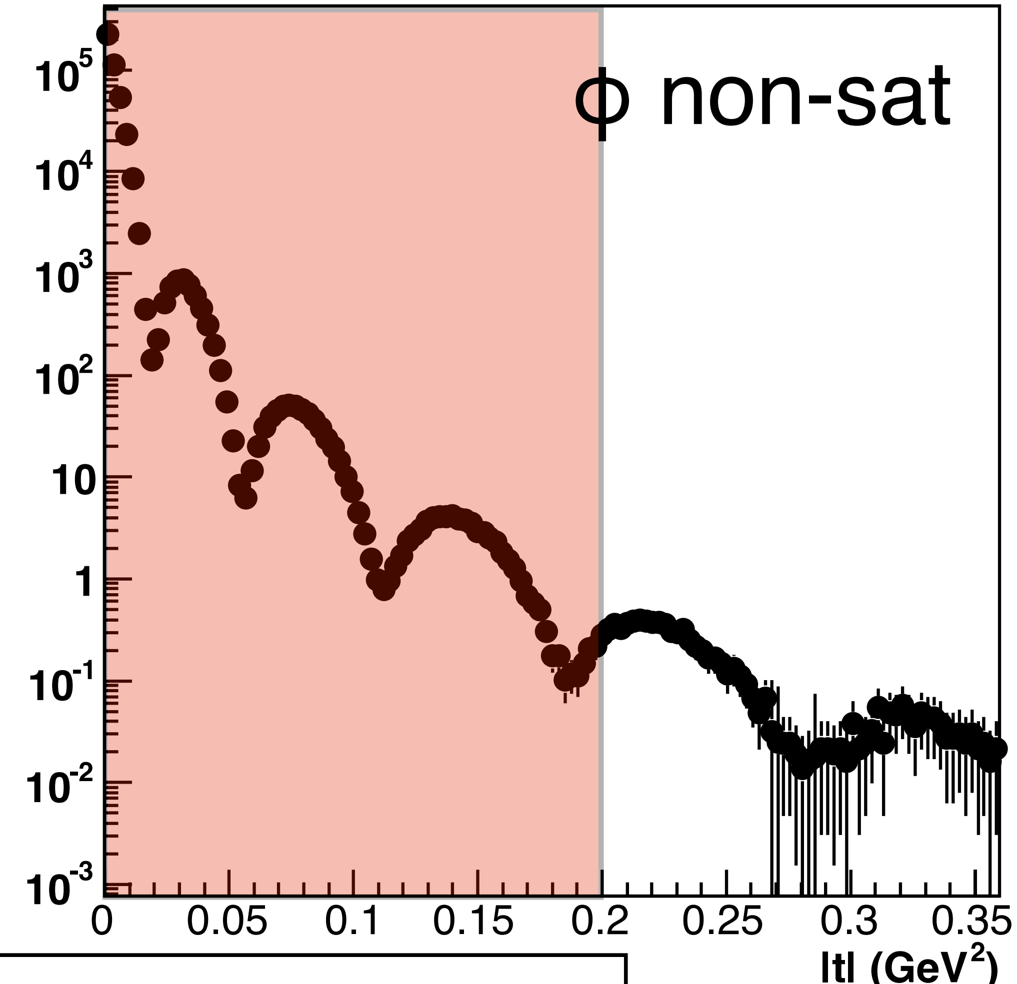

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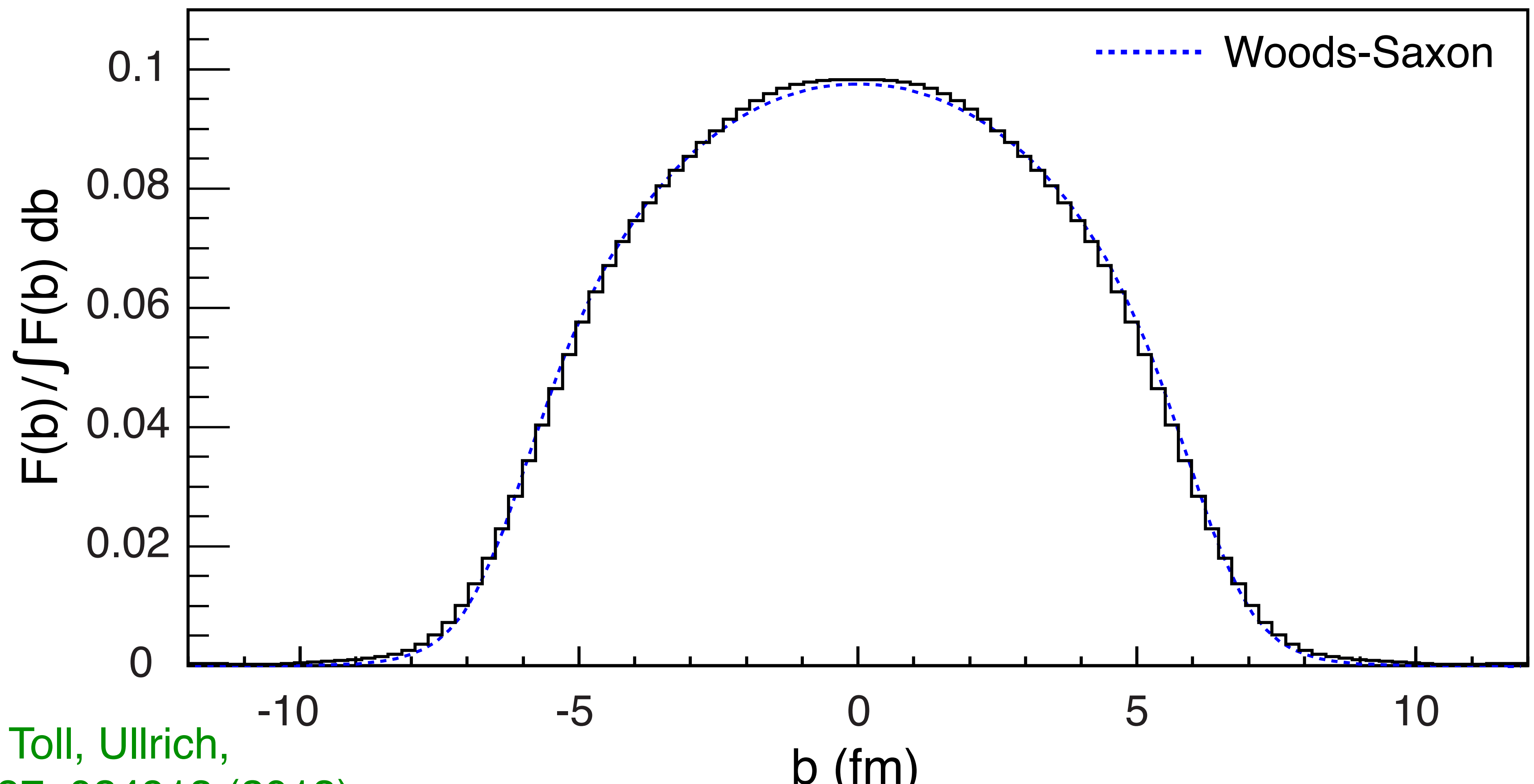

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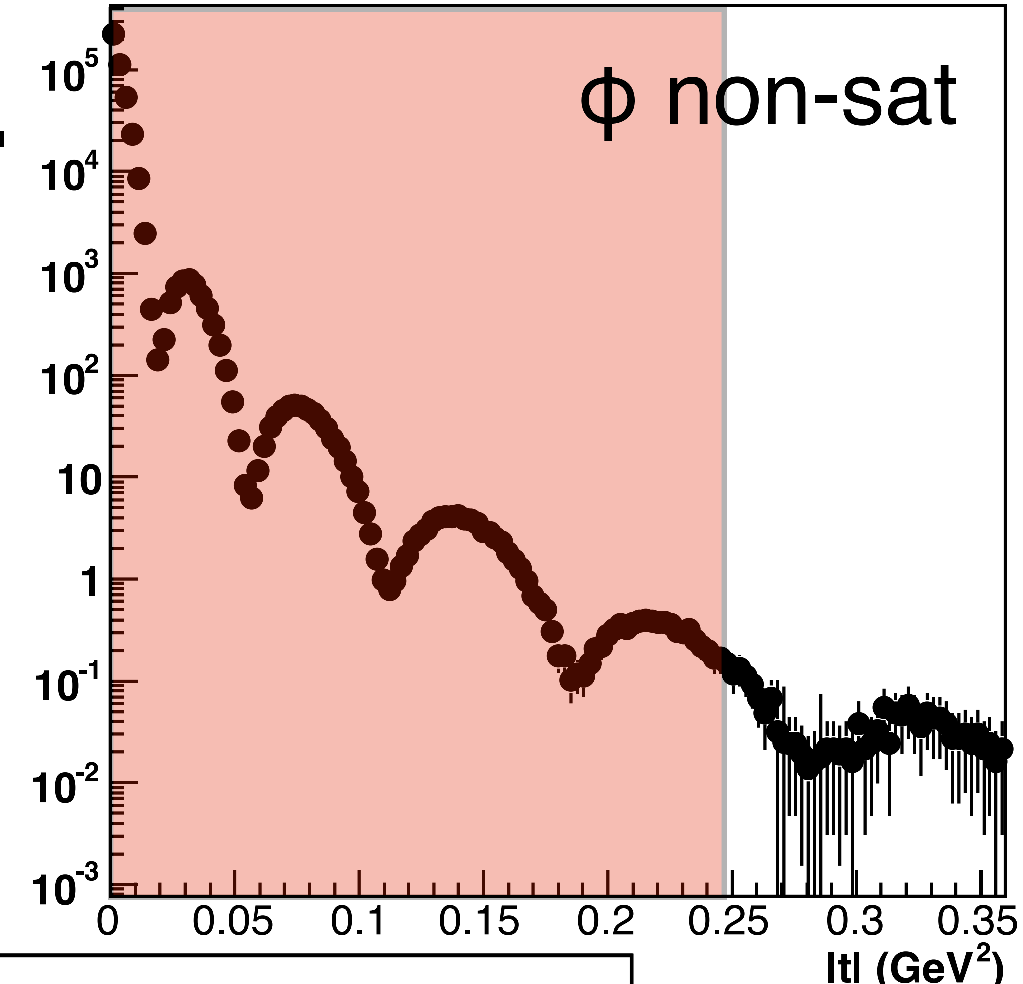

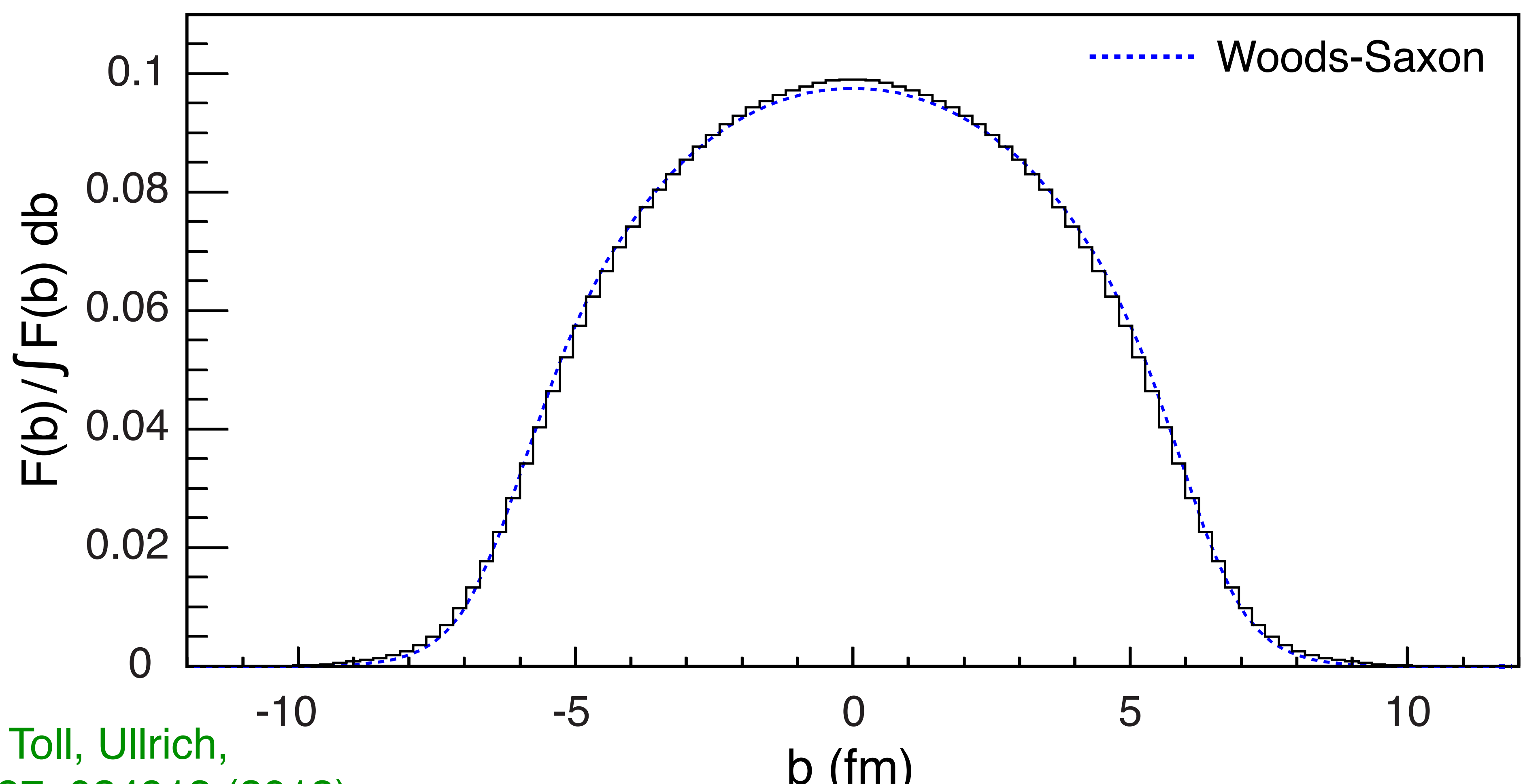

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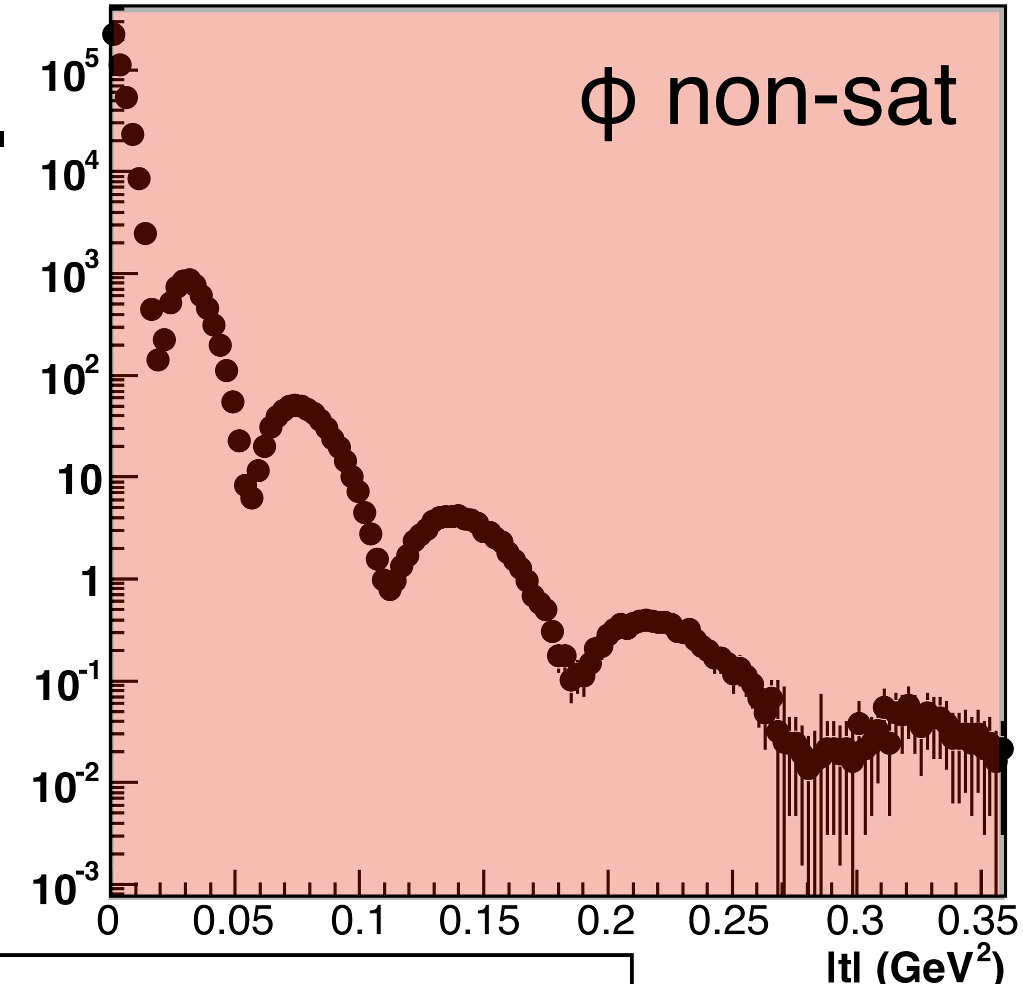

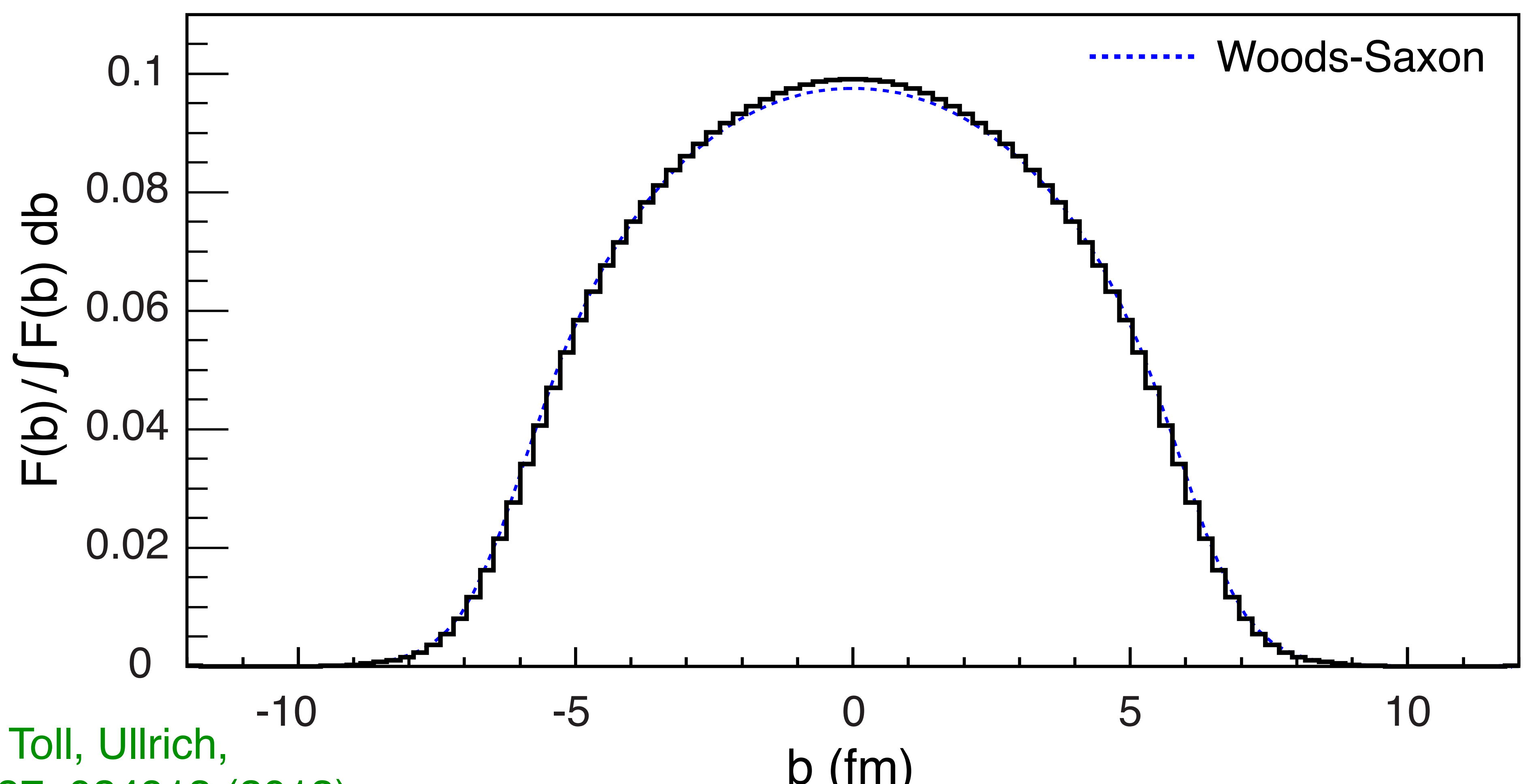

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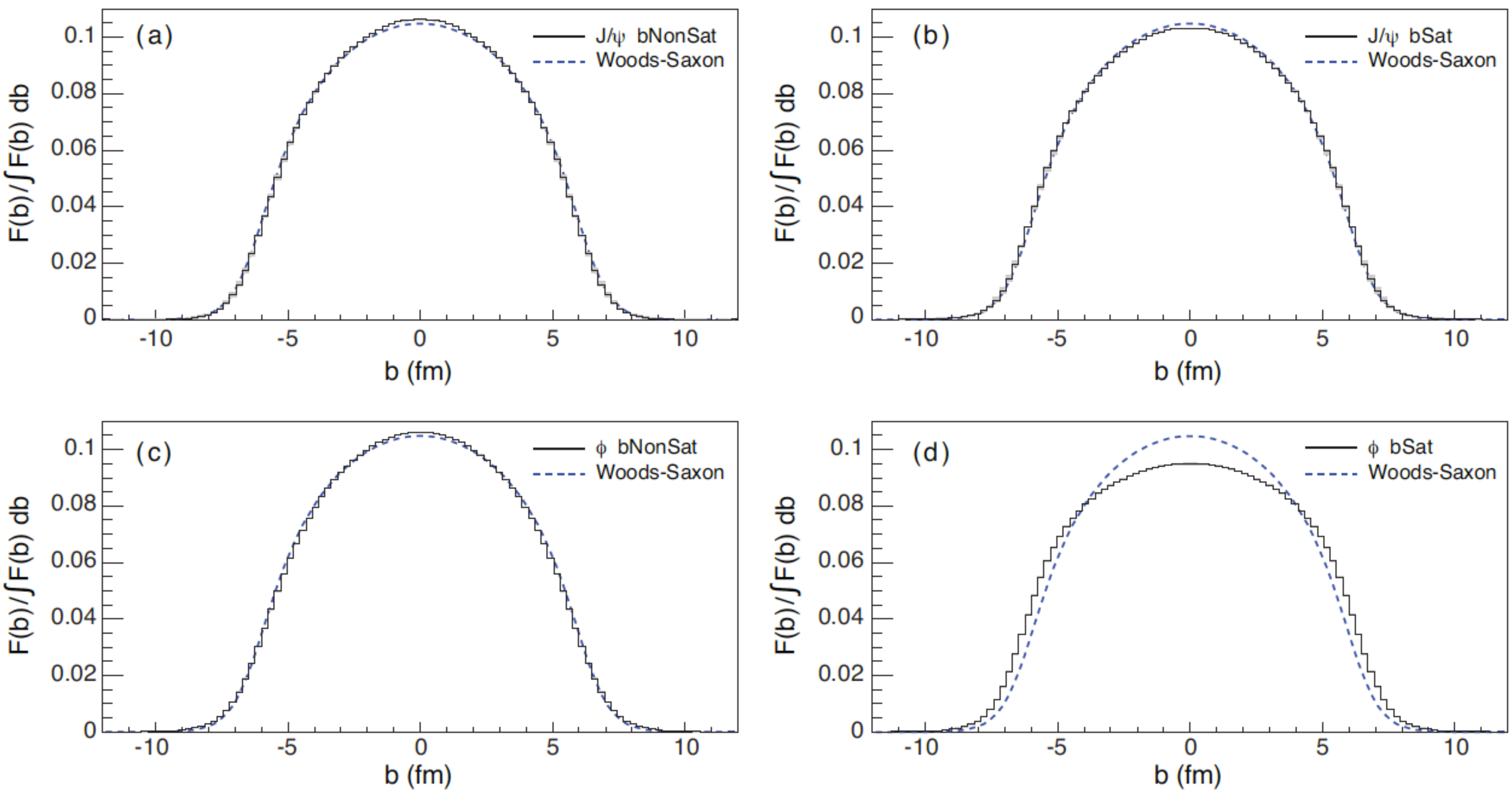
Finding the source...

- J/ψ shows little difference for both saturated and non-saturated modes.
- ϕ shows a significant difference



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- Other important observables not discussed due to time limitations:
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entire science programme is uniquely tied to a future high-energy electron-ion collider

never been measured before & never without

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BACKUP

What is eRHIC?

Electron accelerator

(to be built)

Unpolarized and polarized leptons
15.9, 21.2 GeV

e^-

e^-

e^+

70% e^- beam polarization goal

polarized positrons?

RHIC

Existing = $2B

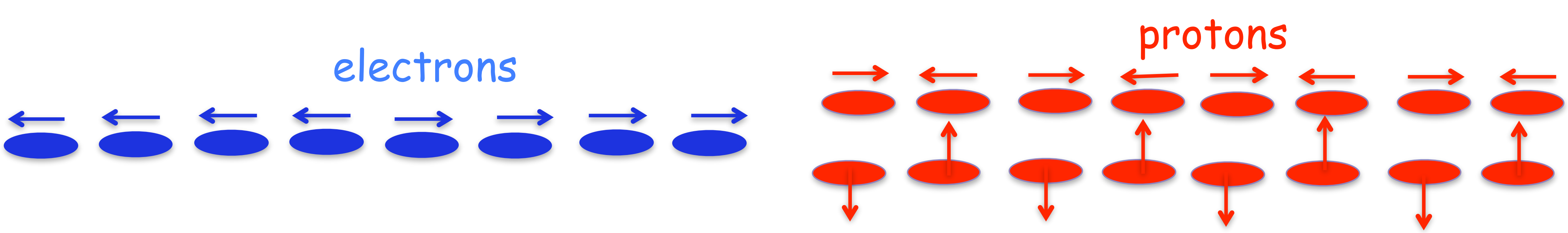
p

Polarized protons
50-250 GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 GeV/u

Polarized light ions He^3
166 GeV/u

Center mass energy range: $\sqrt{s}$=30-200 GeV; L~100-1000xHera
longitudinal and transverse polarization for p/He^3 possible



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- Understanding the role of gluons in nuclei is crucial to understanding RHIC and LHC results
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  - ➡ Constrain $\Delta g(x)$ at small x along with the flavour-separated helicity PDFs
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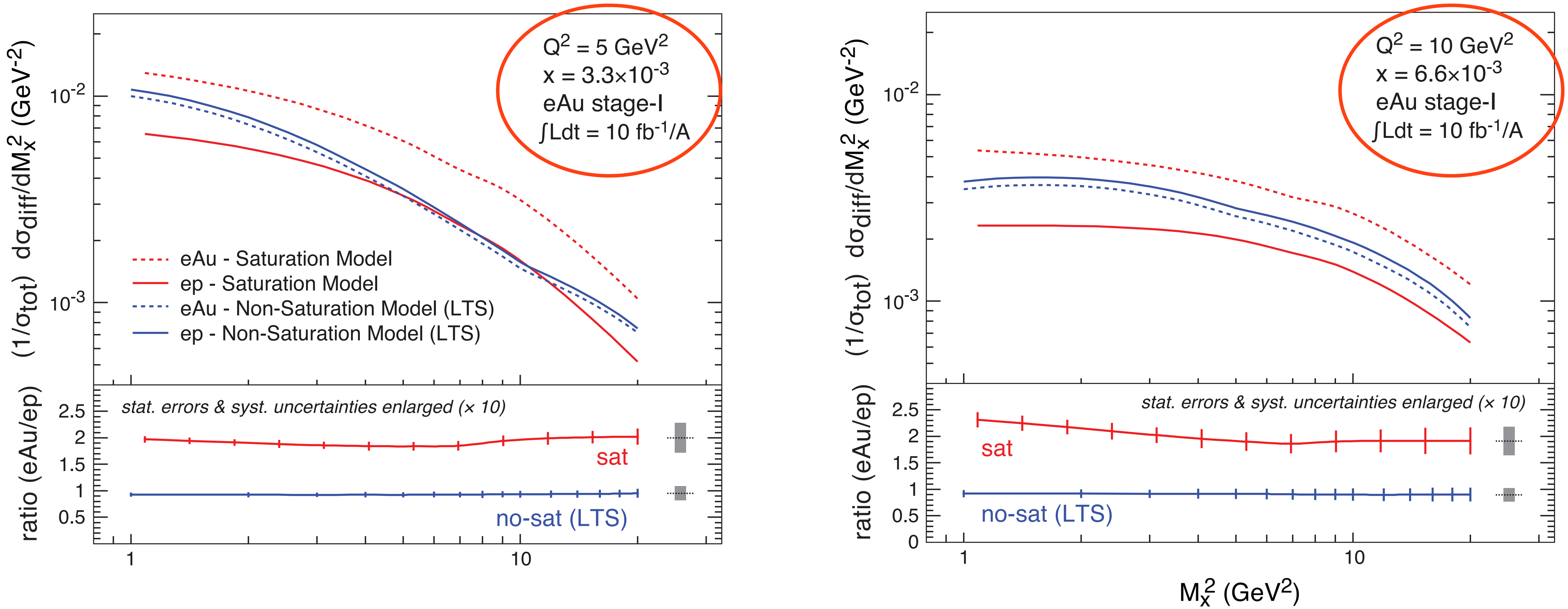
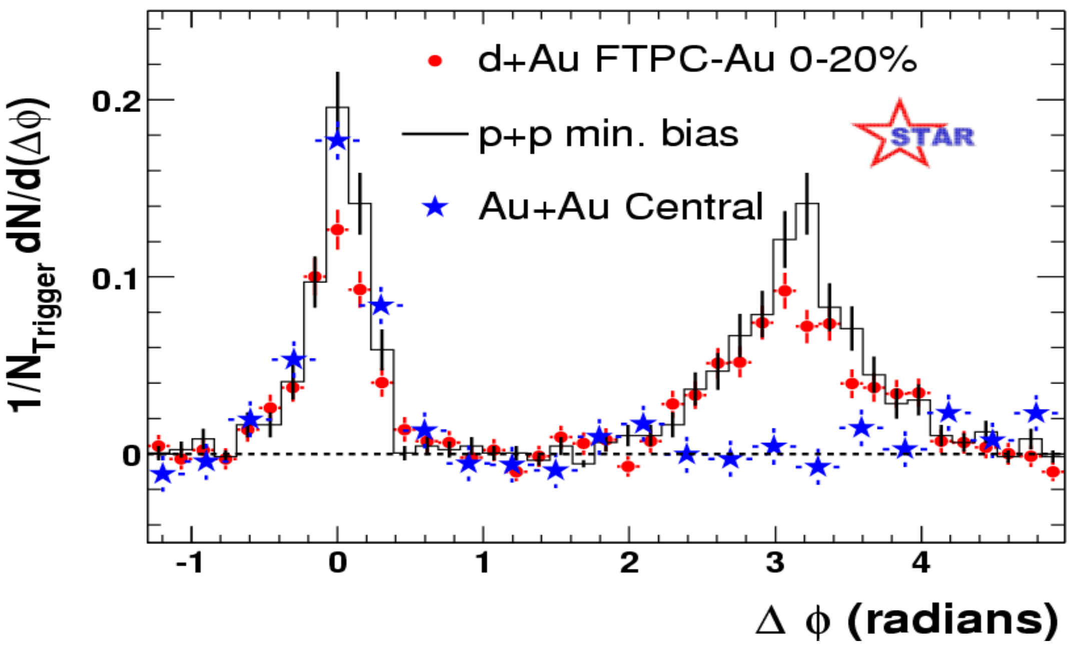
Day 1: Diffractive Cross-sections

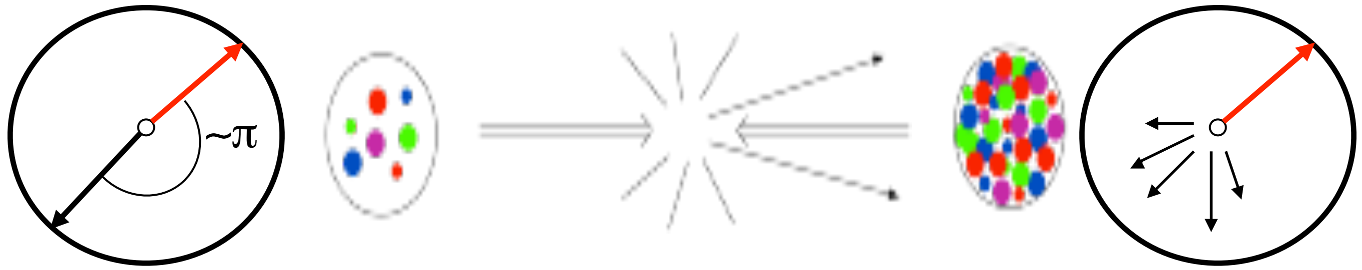


- Ratio of diffractive-to-total cross-section drastically different between saturation (Marquet) and non-saturation (Frankfurt, Guzey, Strikman) models
- Expected experimental error bars (simulated for 10 fb^{-1} of data for a low-energy eRHIC) can distinguish between the two scenarios

di-hadron correlations in d+A

comparisons between d+Au → h_1 h_2 X (or p +Au → h_1 h_2 X) and p+p → h_1 h_2 X





- At y=0, suppression of away-side jet is observed in A+A collisions
- No suppression in p+p or d+A

➡x ~ 10^{-2}

$$x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} << 1$$

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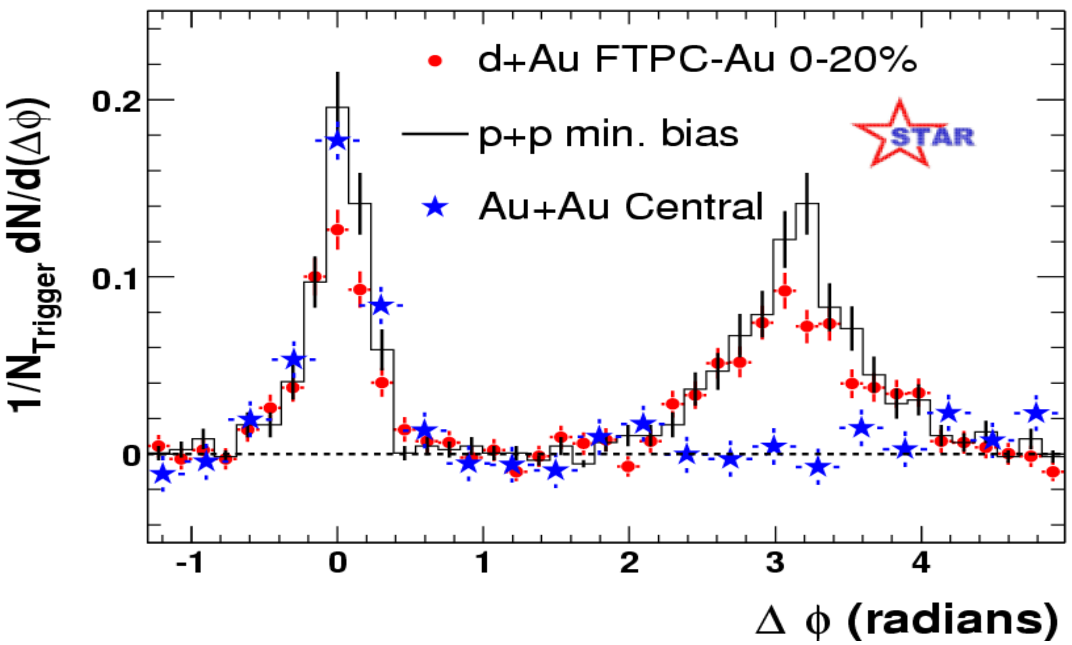

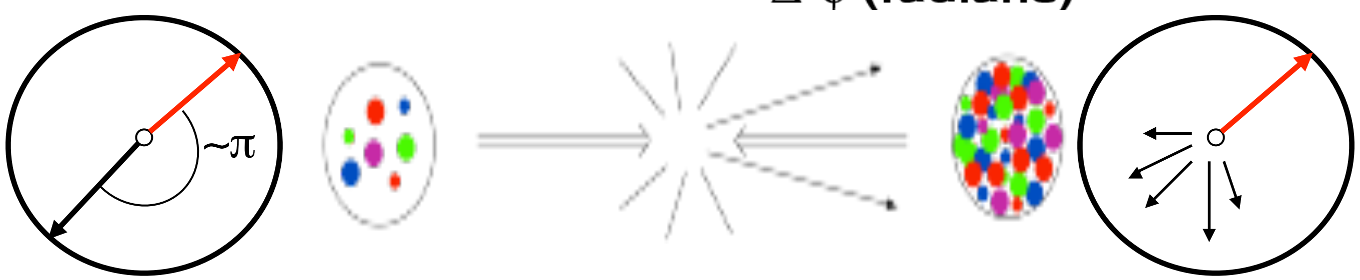

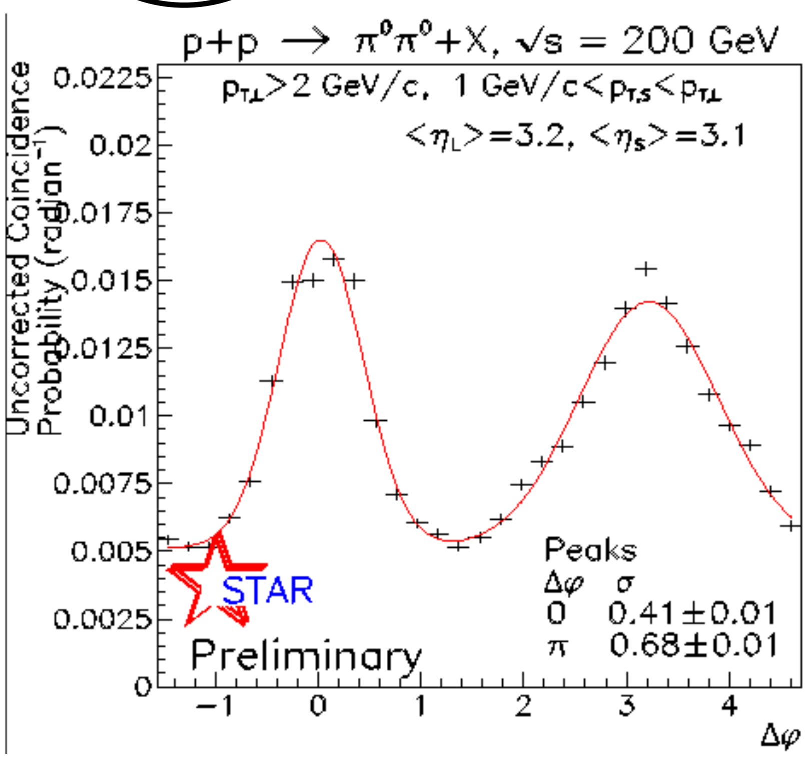

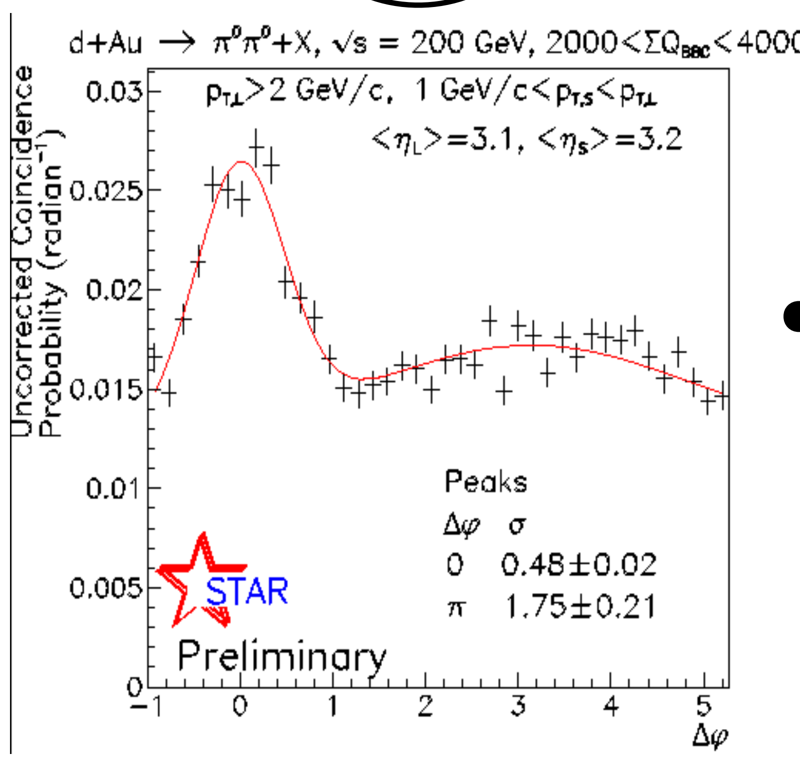

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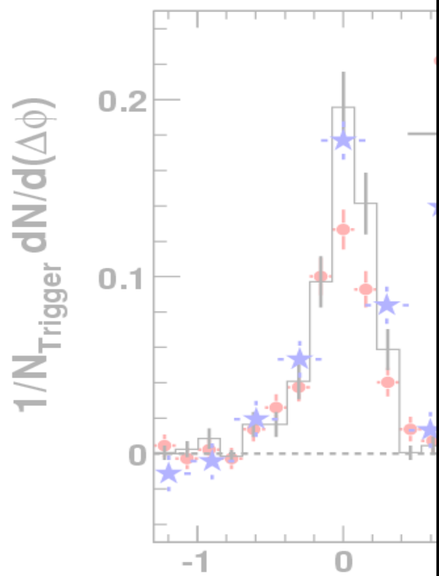
- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p

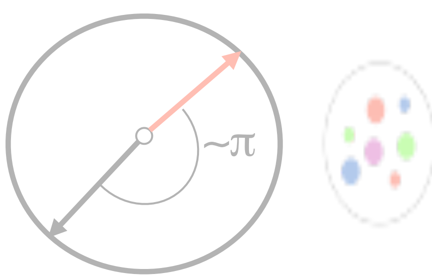
➡ x ~ 10^{-3}

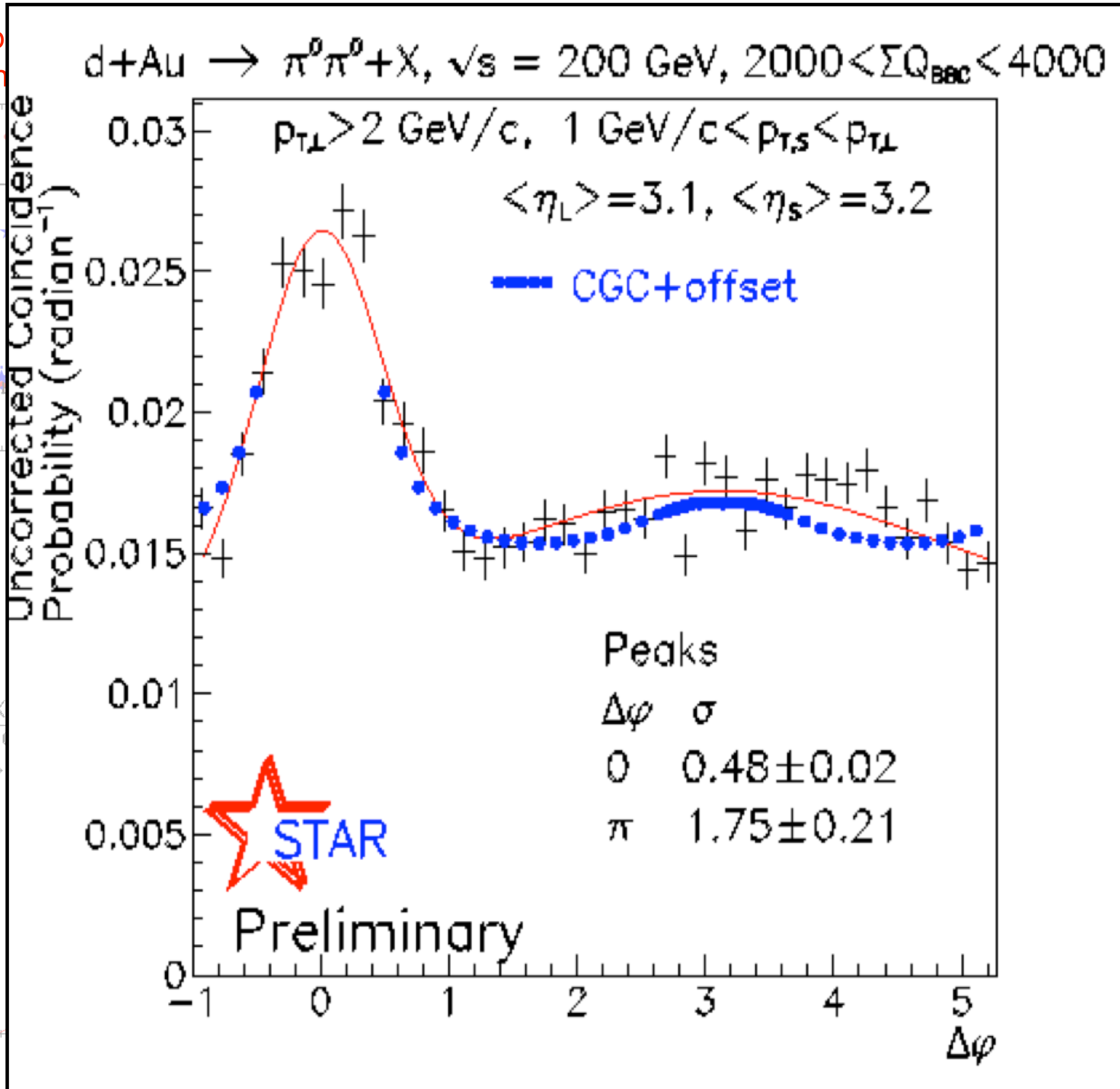
l.gov

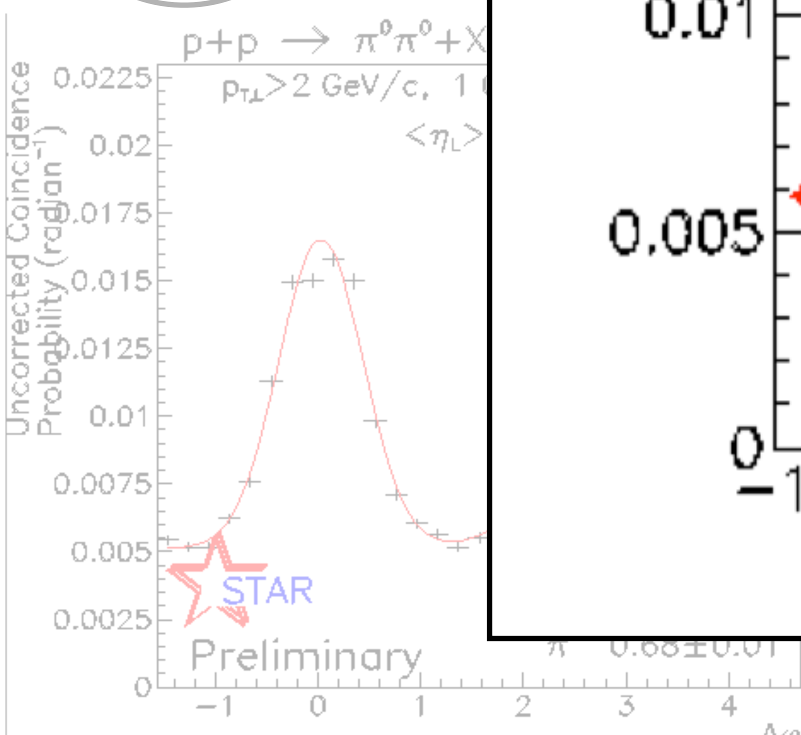
di-hadron correlations in d+A

comparisons b
+Au → h_1 h









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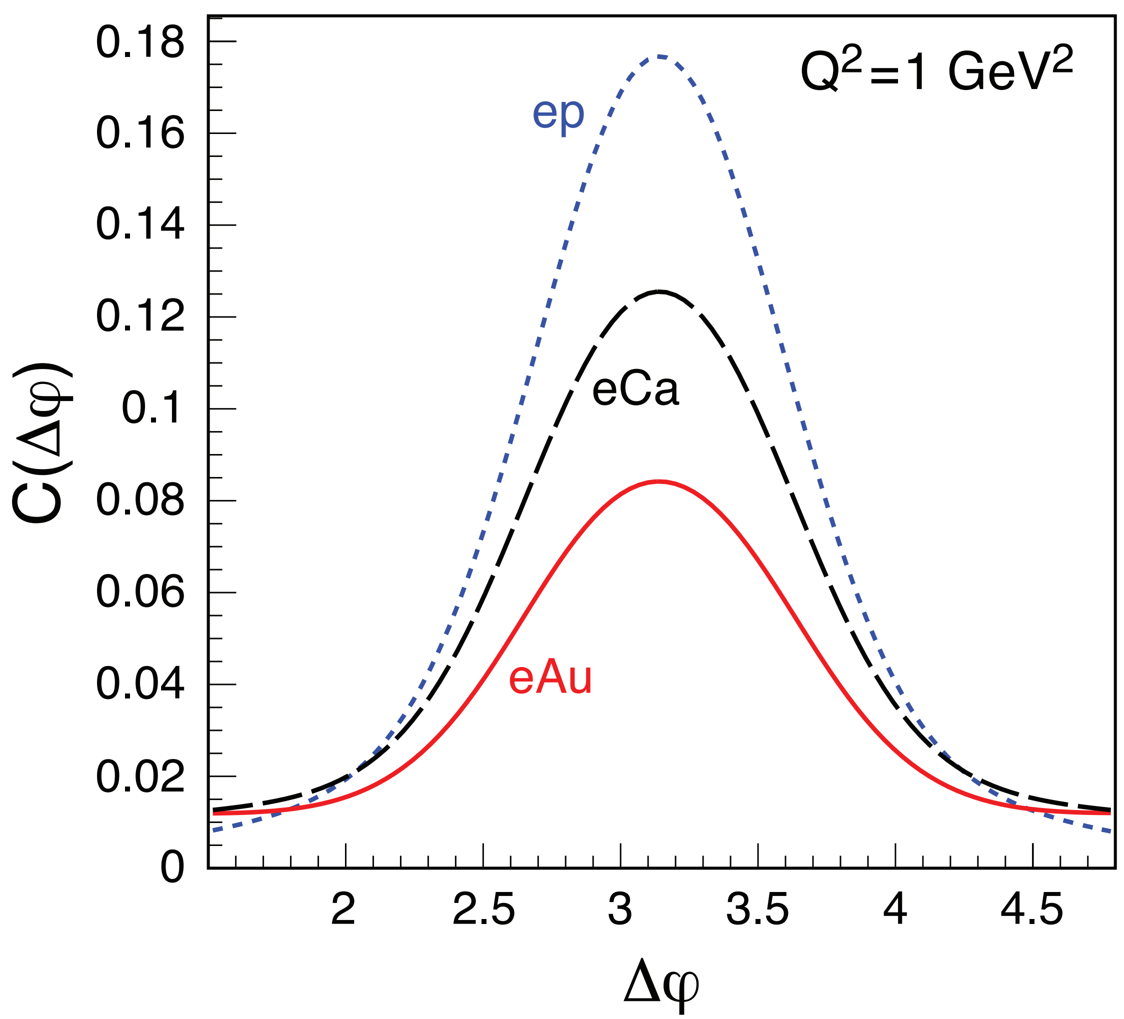

Dominguez, Xiao and Yuan (2012)

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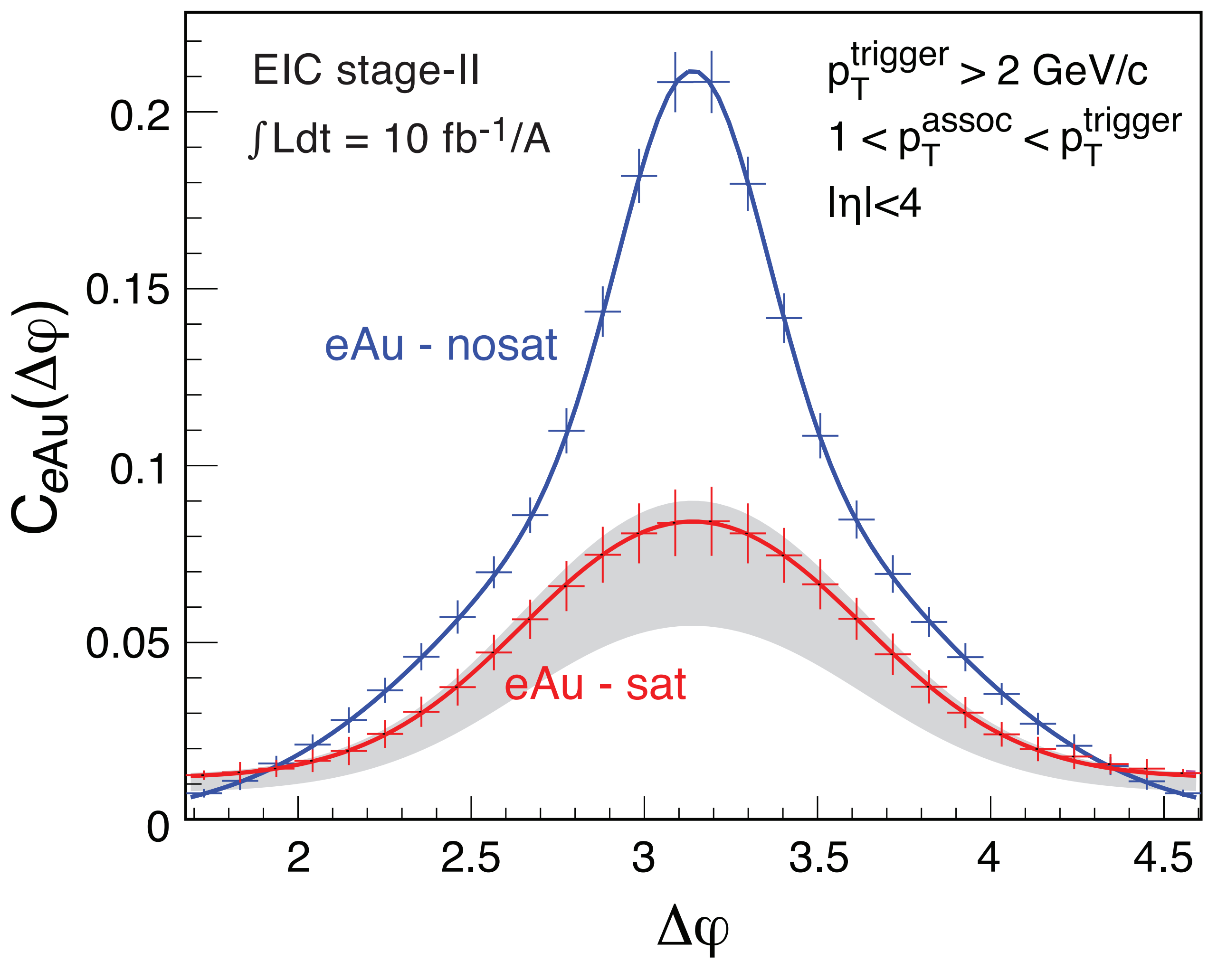

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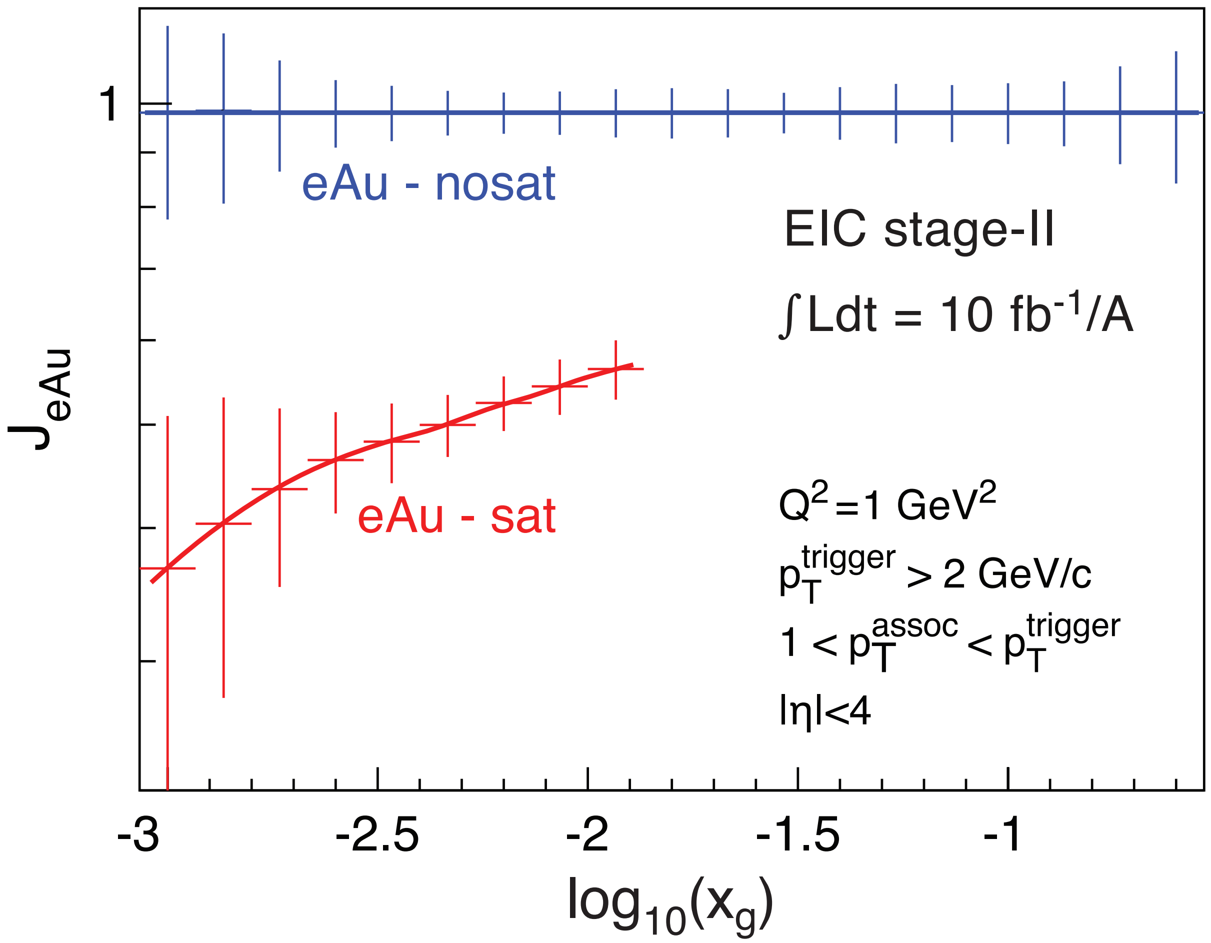
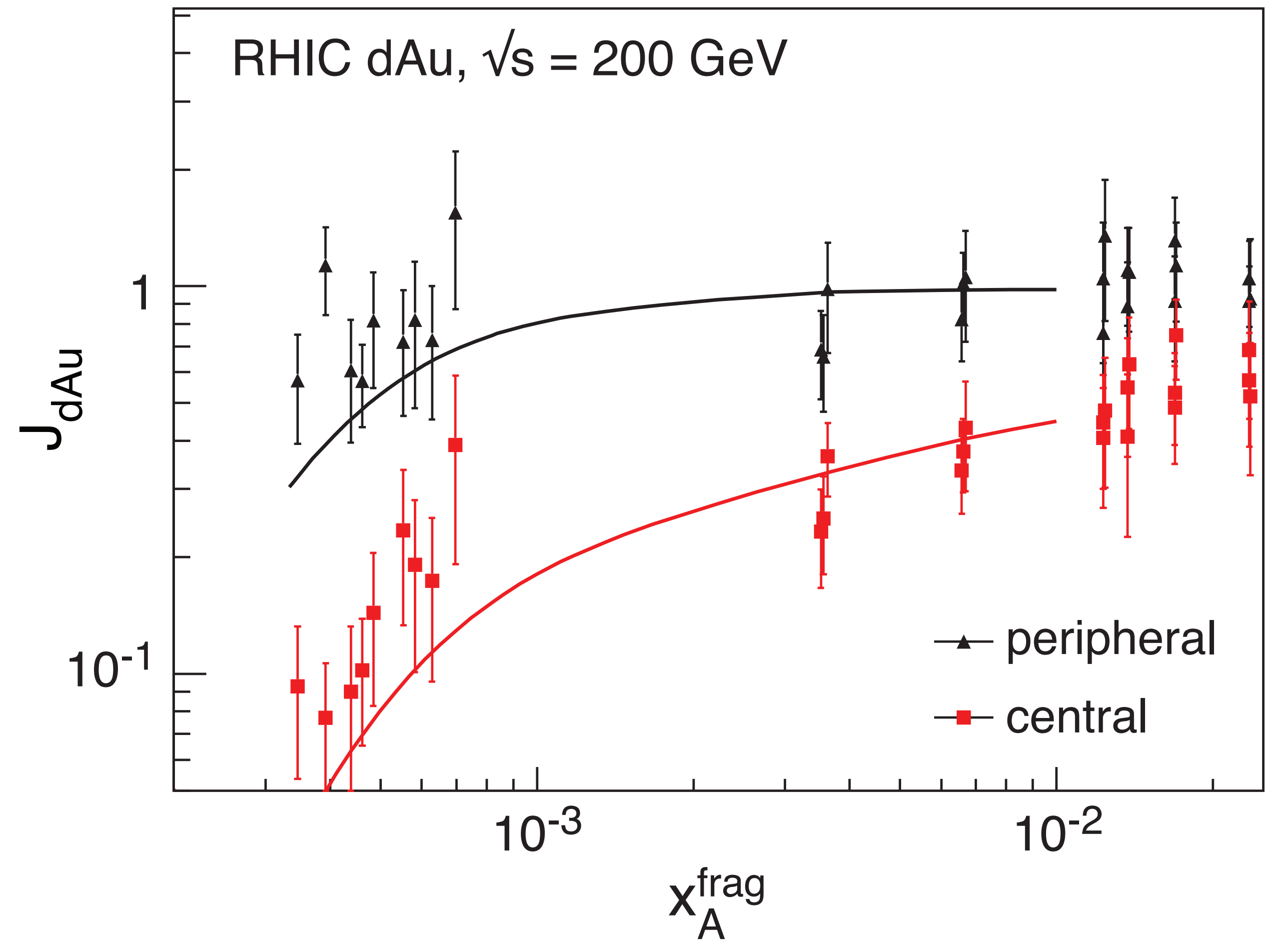
di-hadron Correlations - relative yields

- PHENIX measured J_{dAu} - relative yield of di-hadrons produced in d+Au compared to p+p collisions
  - ➡ Suppression in central events compared to peripheral as a function of x_A^{frag}
    - Curves come from saturation model
- Can perform the same measurement in e+A collisions

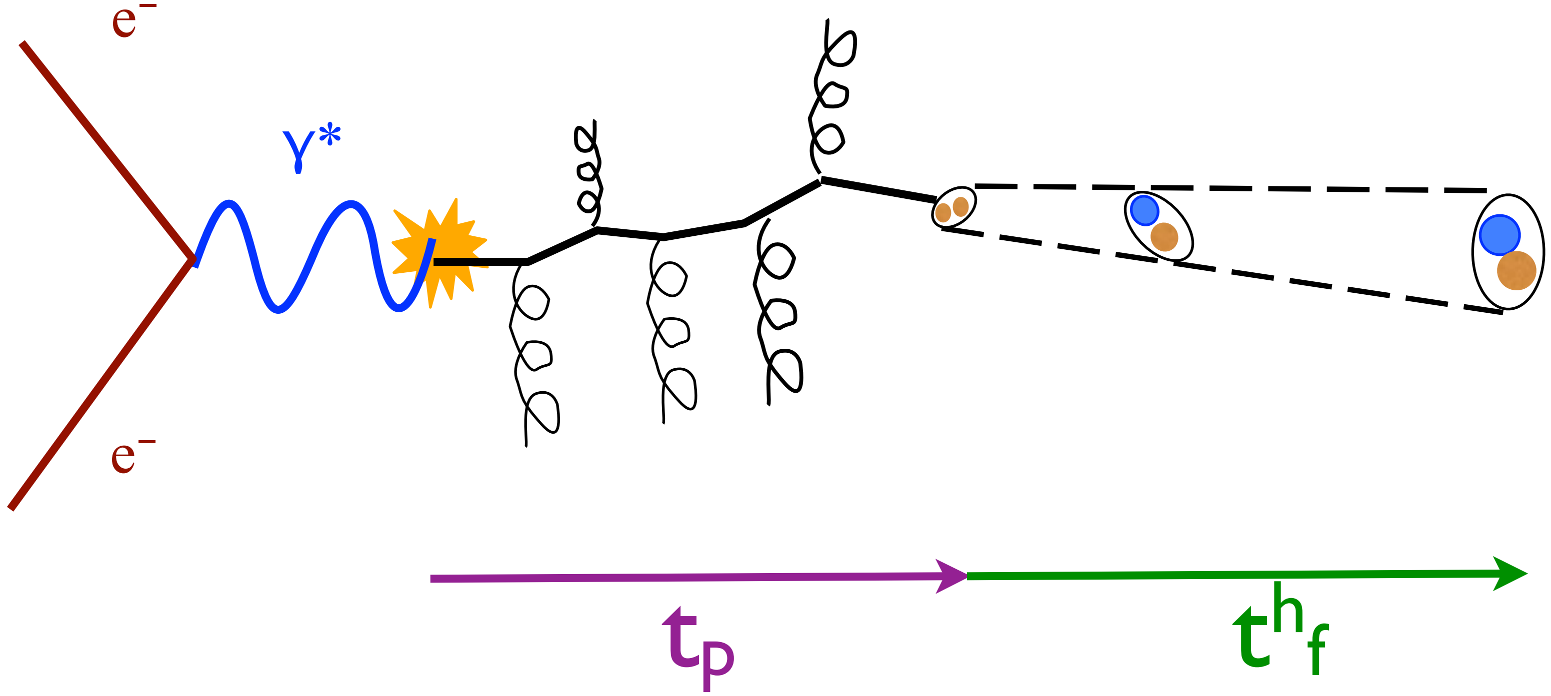


forward-forward mid-forward



A. Adare et al., Phys. Rev. Lett. 107, 172301 (2011)

Jets and hadronization



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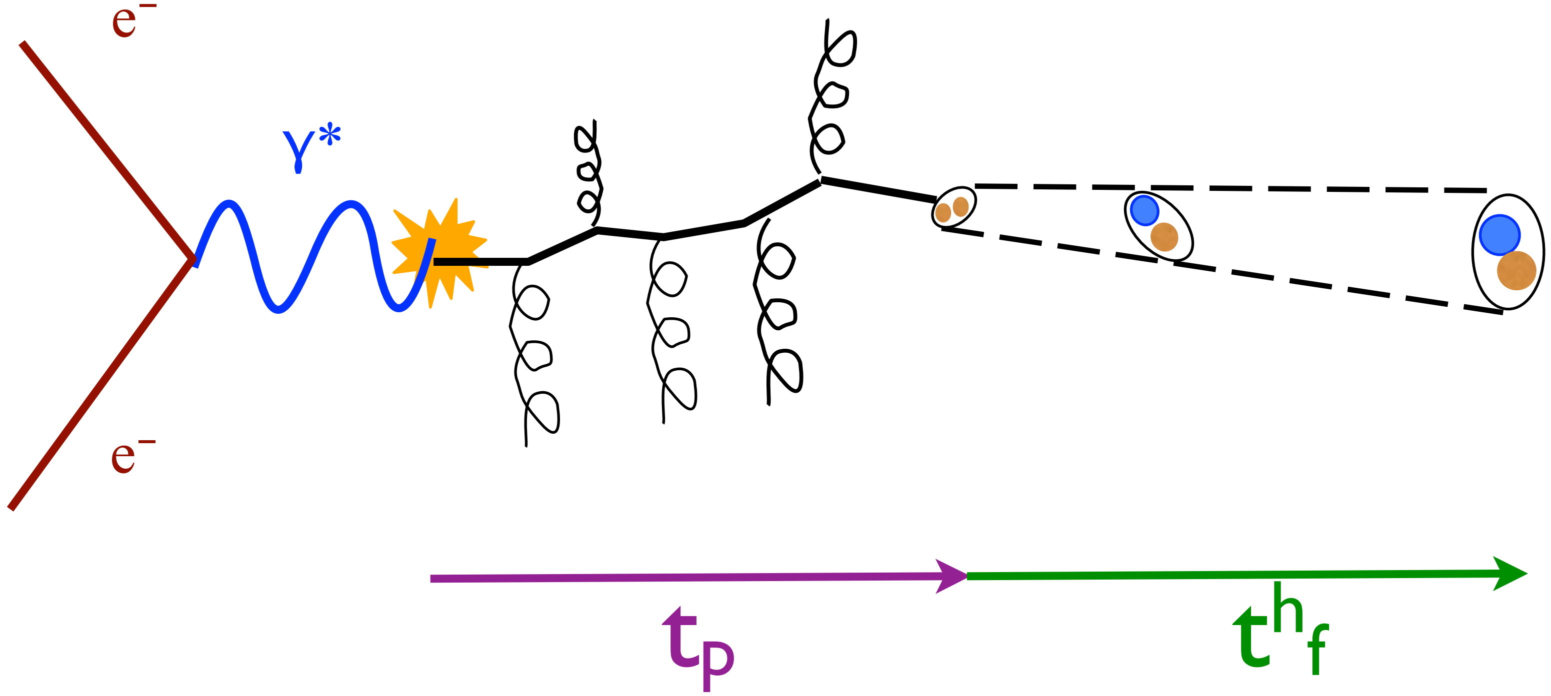

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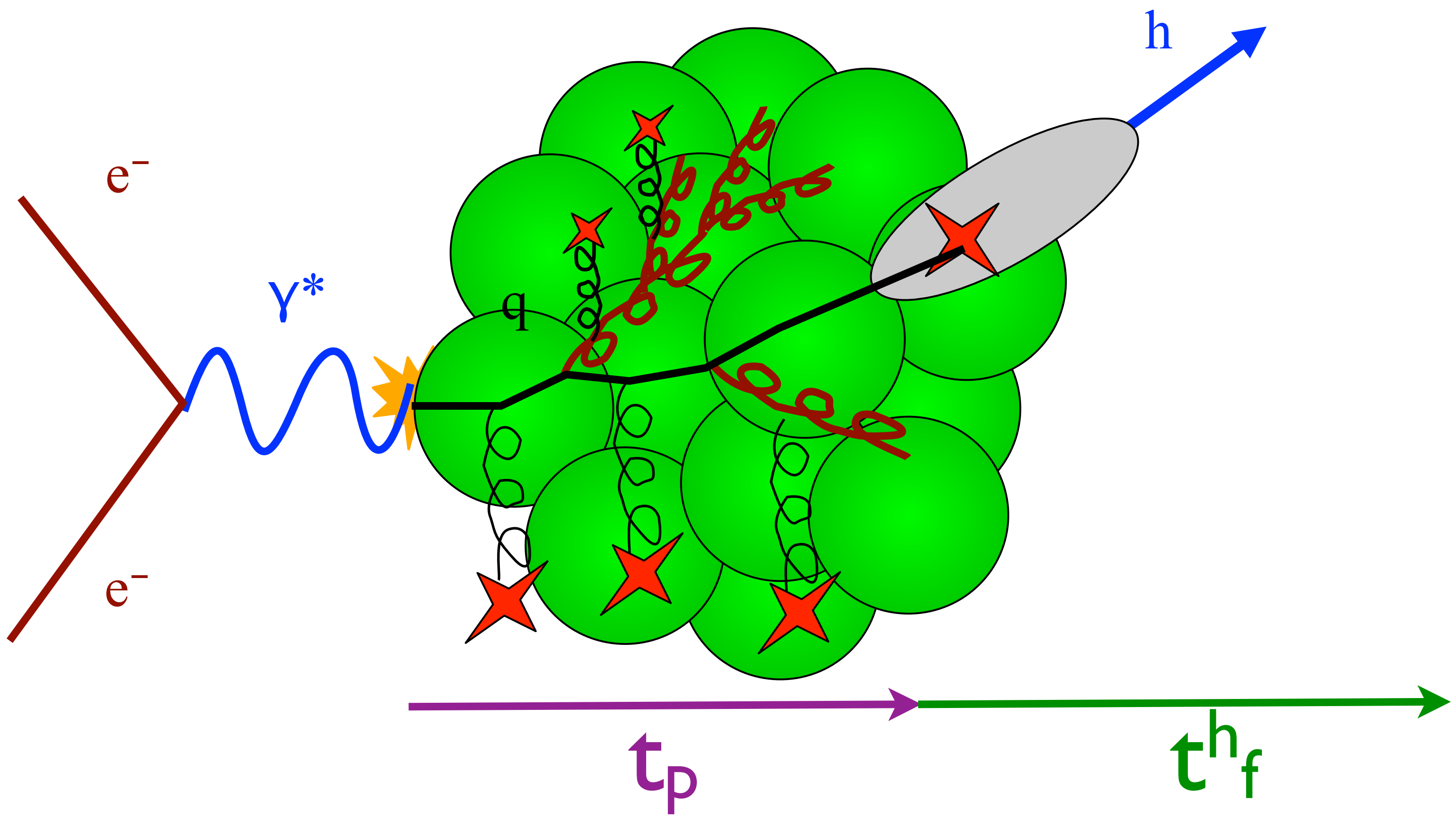

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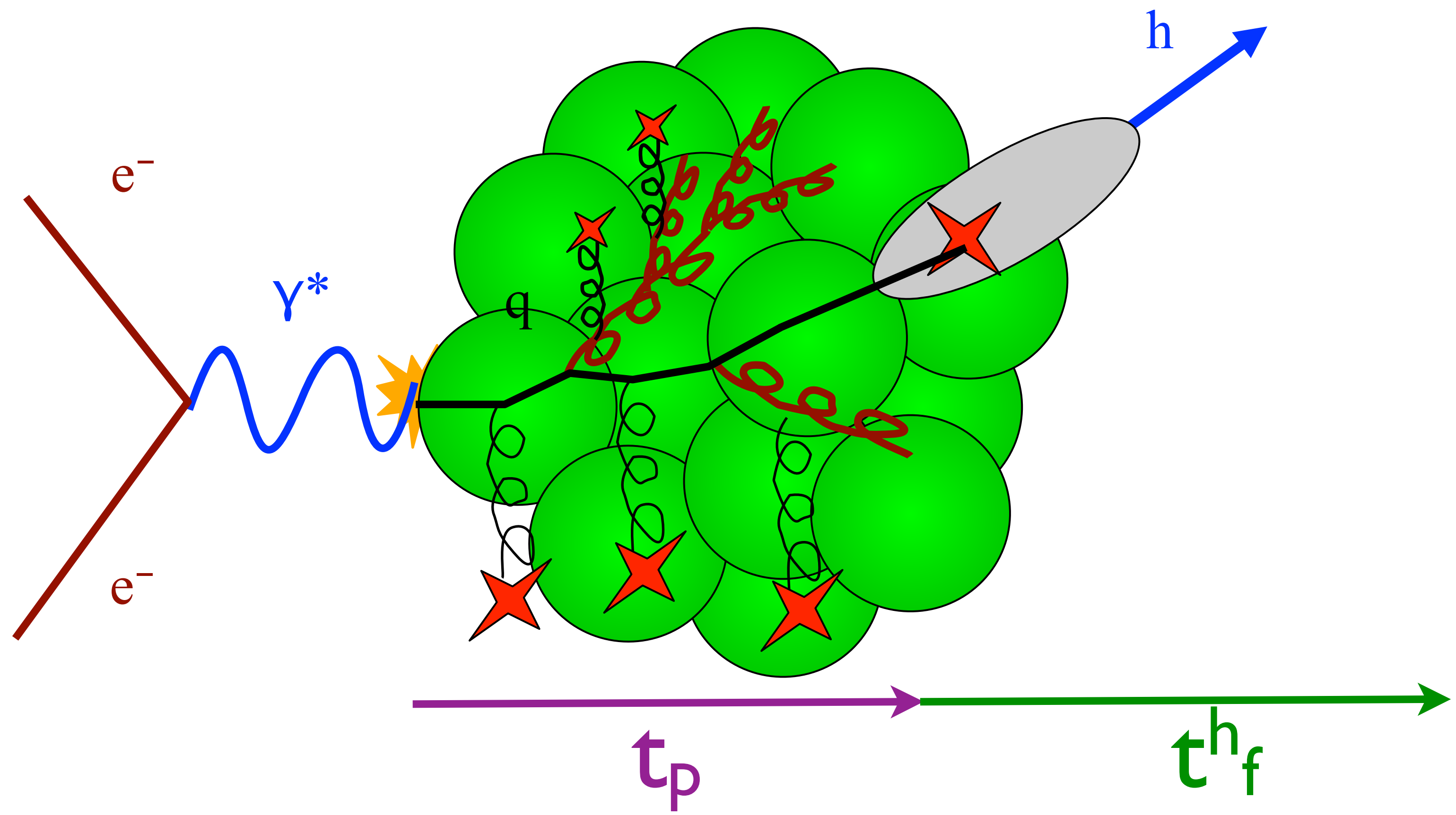

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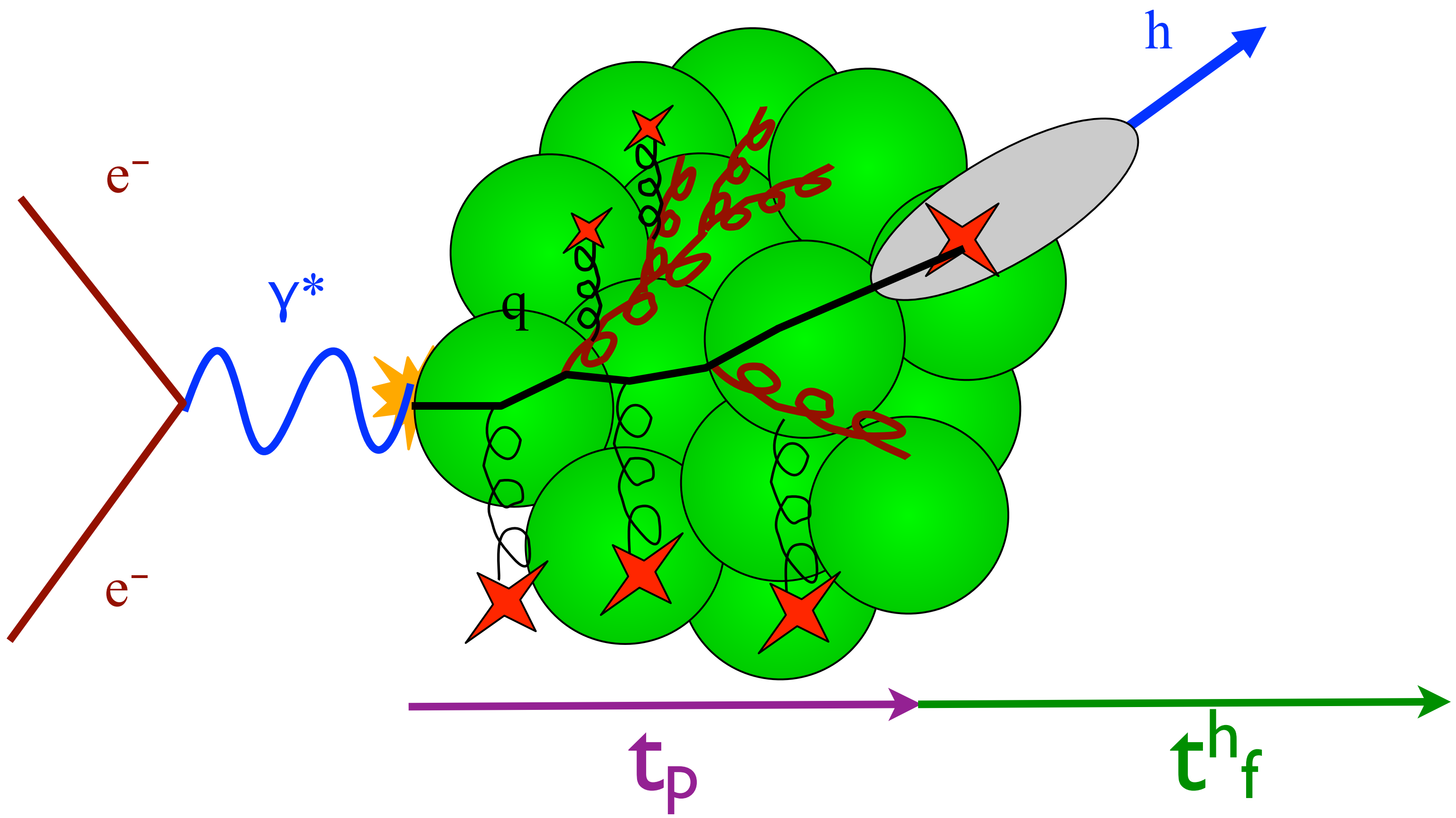

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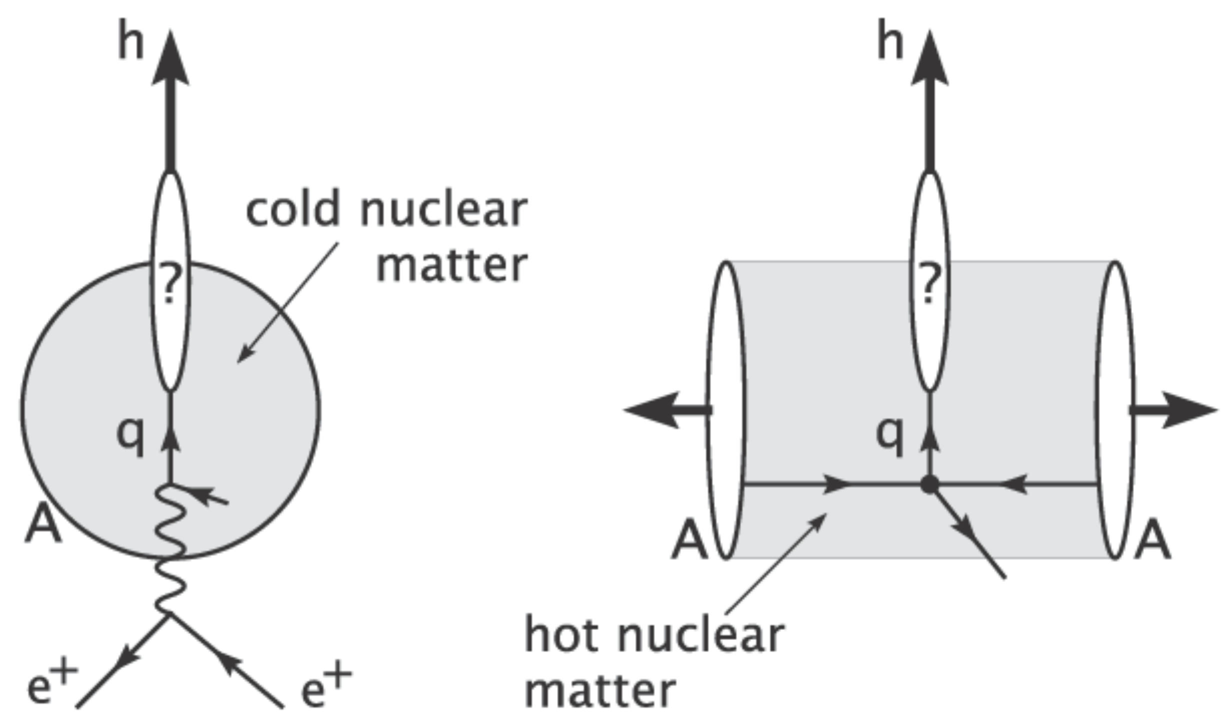

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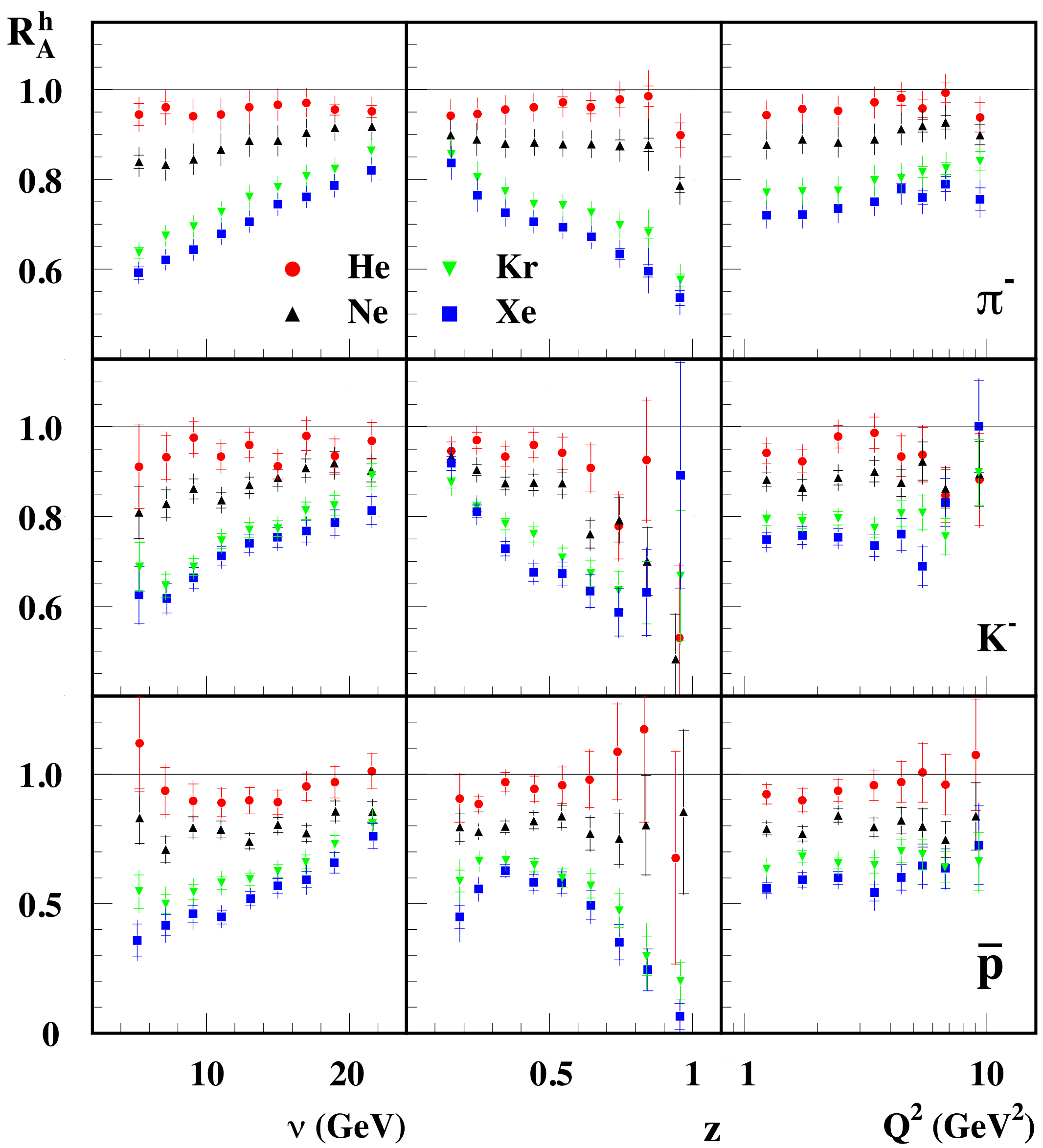
HERMES:

E_e = 27 GeV → $\sqrt{s}$ = 7.2 GeV

E_h = 2-15 GeV



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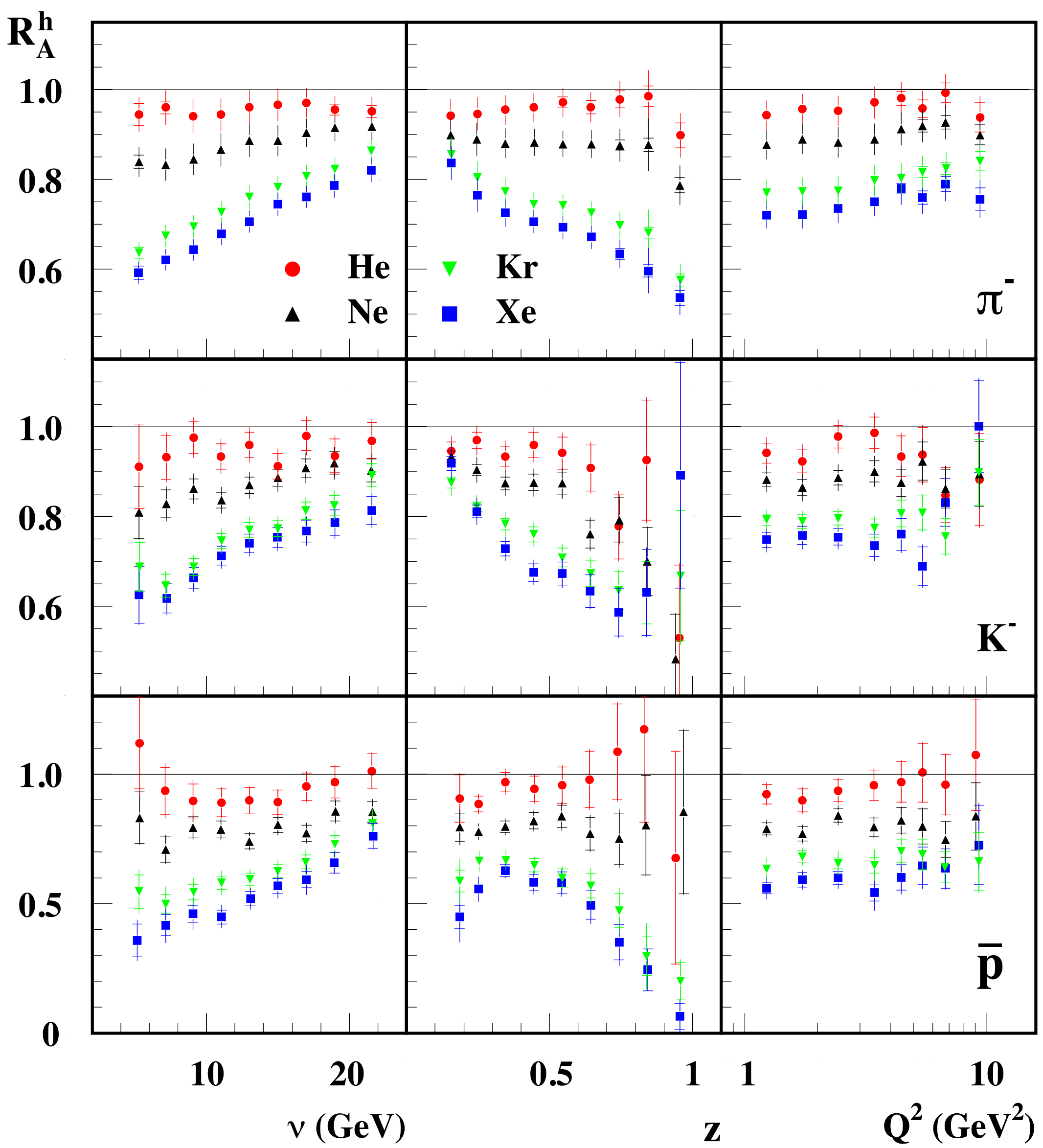

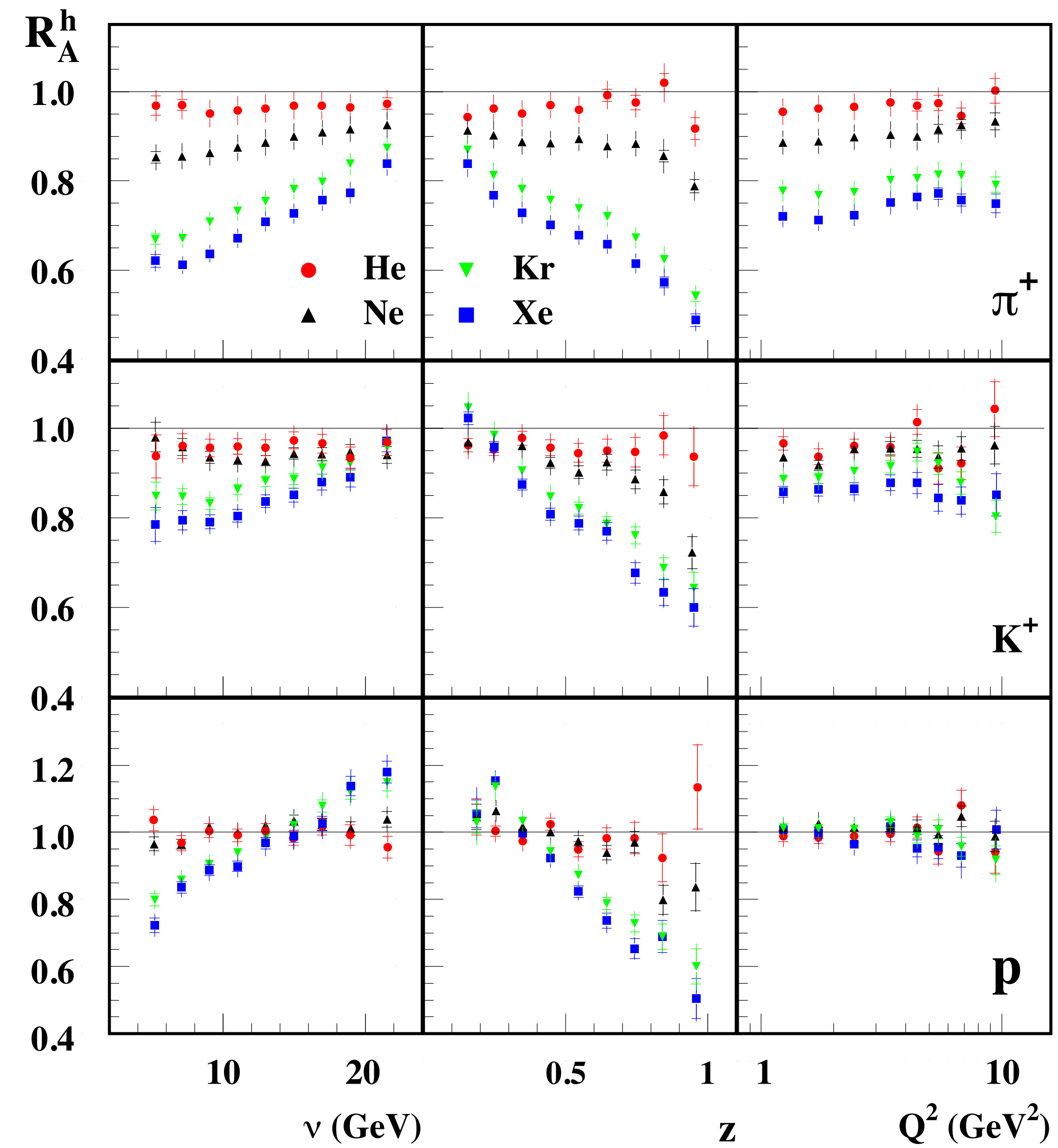

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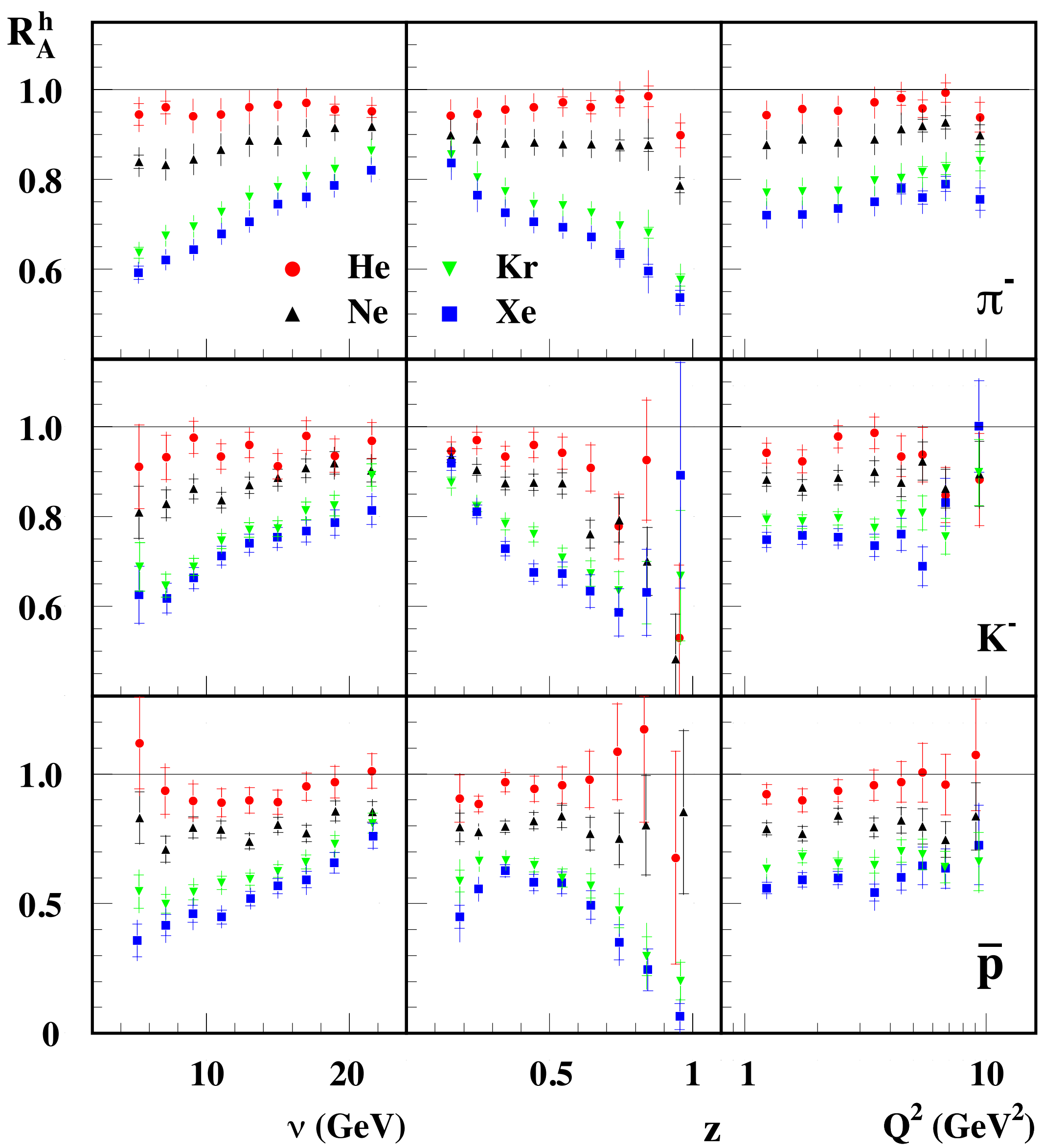

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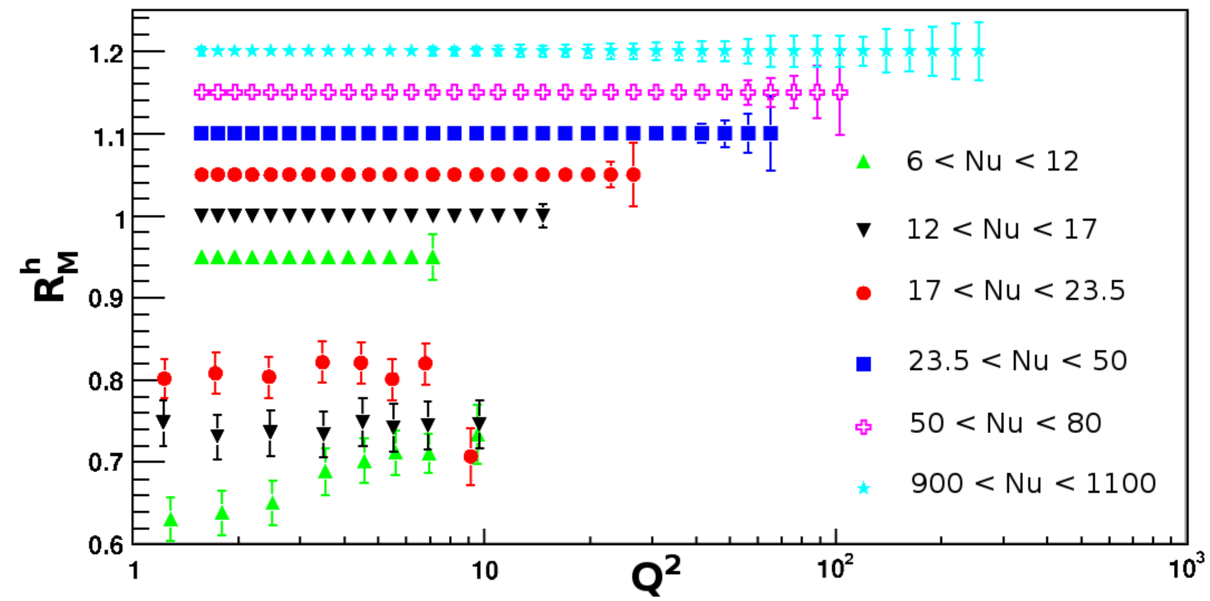

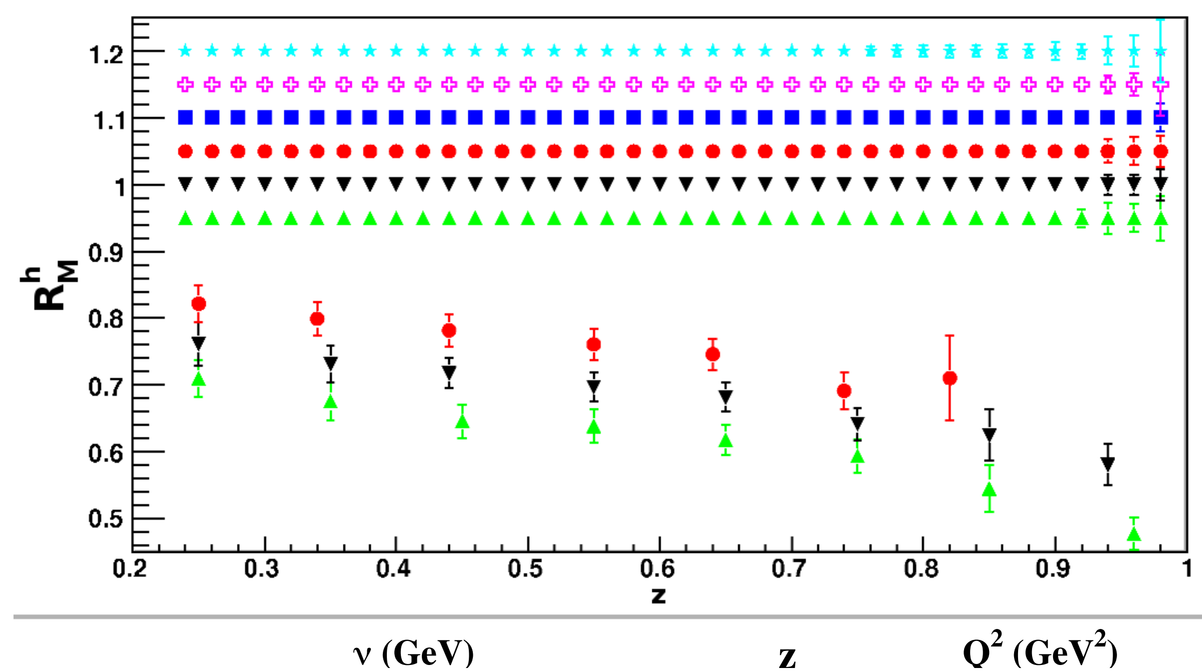

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PANIC 2014: hadronization in and out of nucleus

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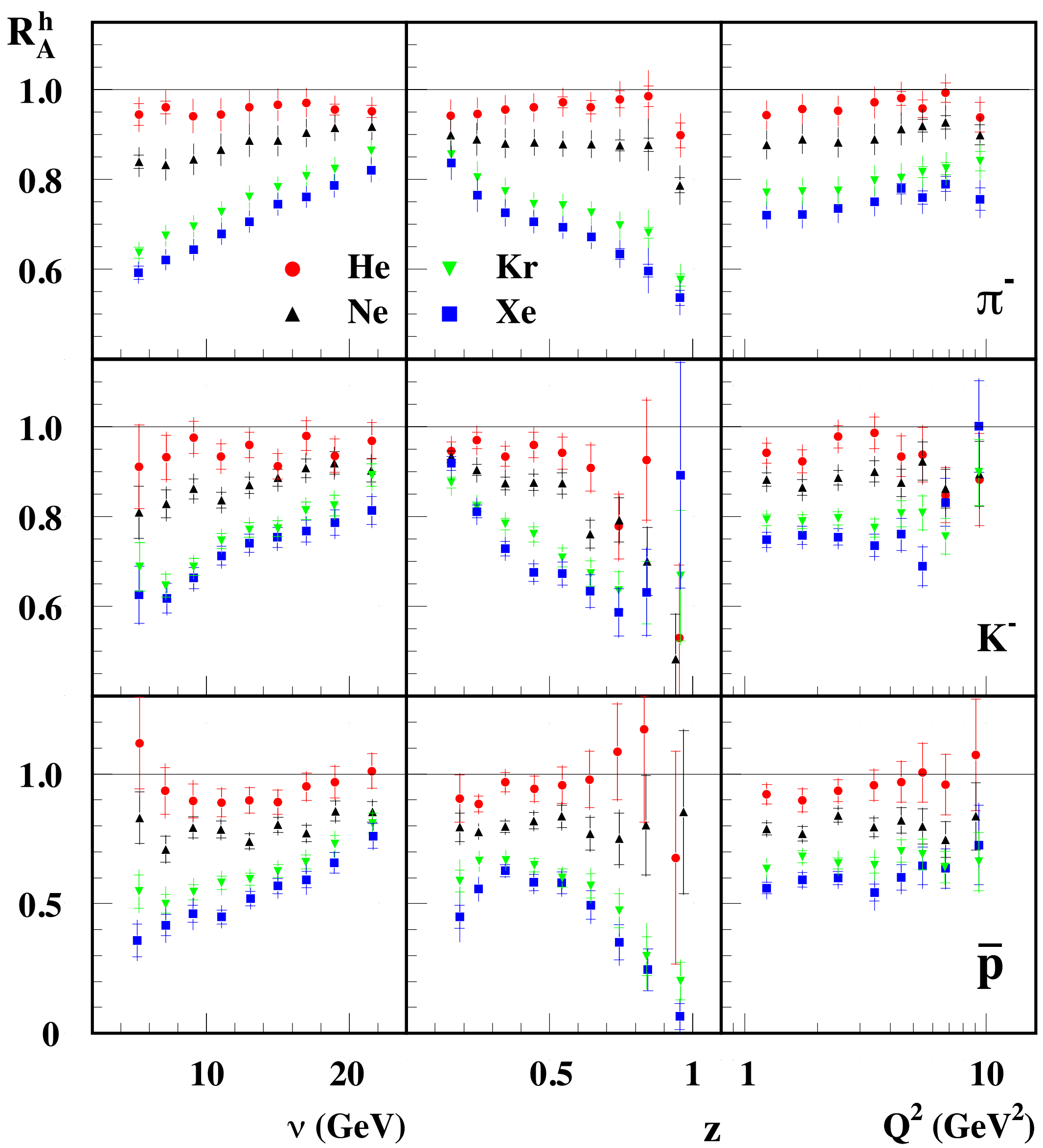

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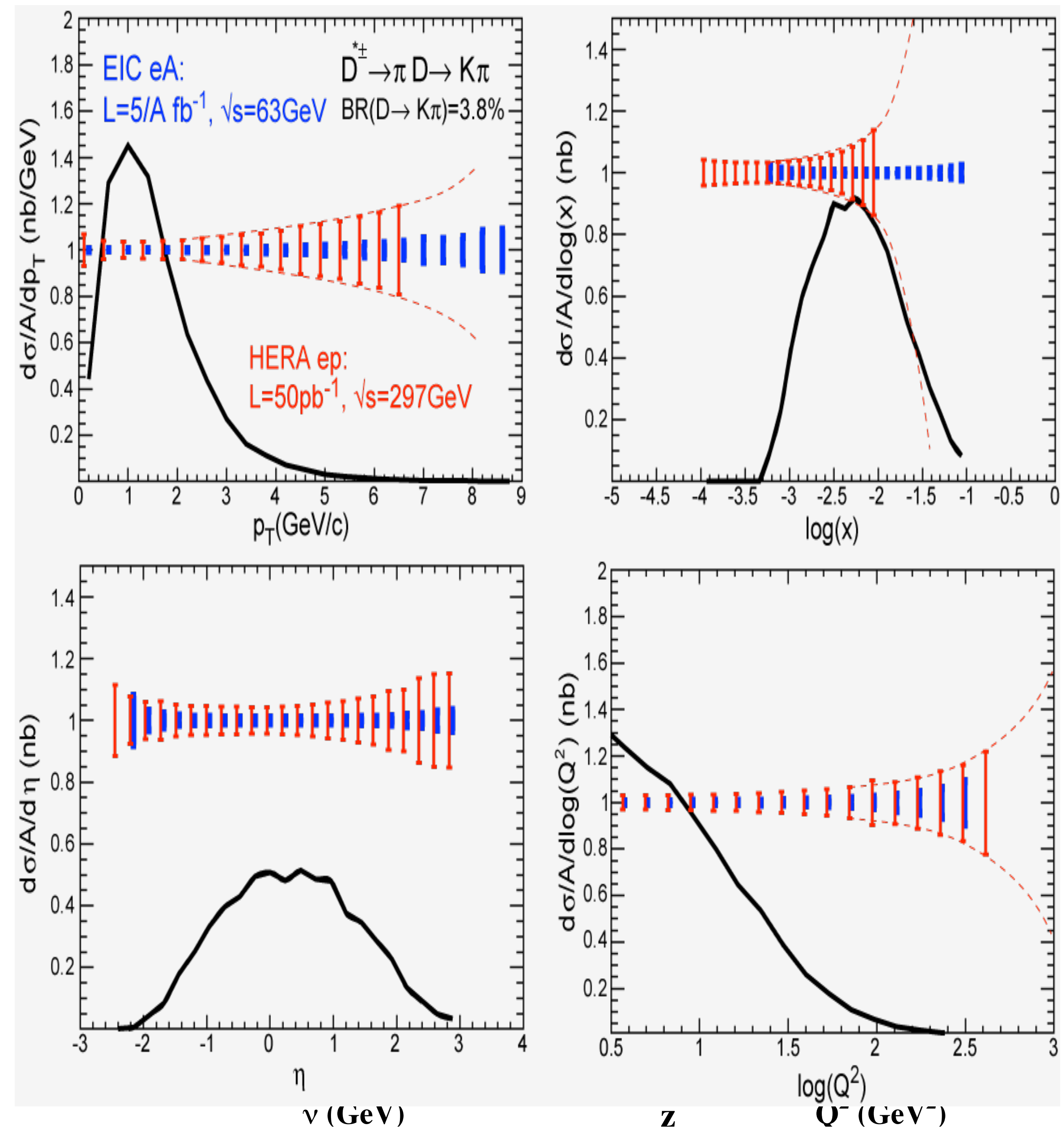

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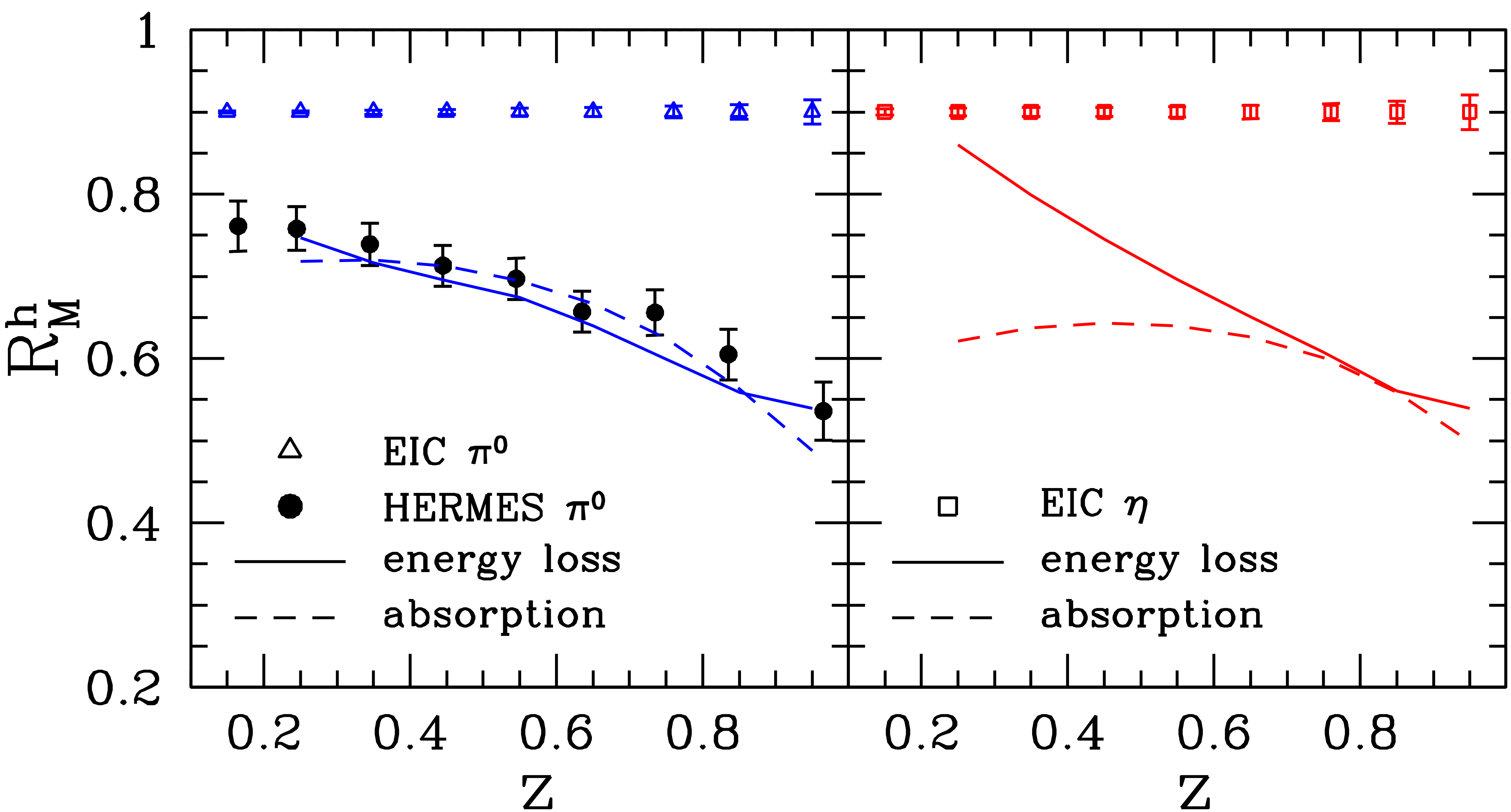

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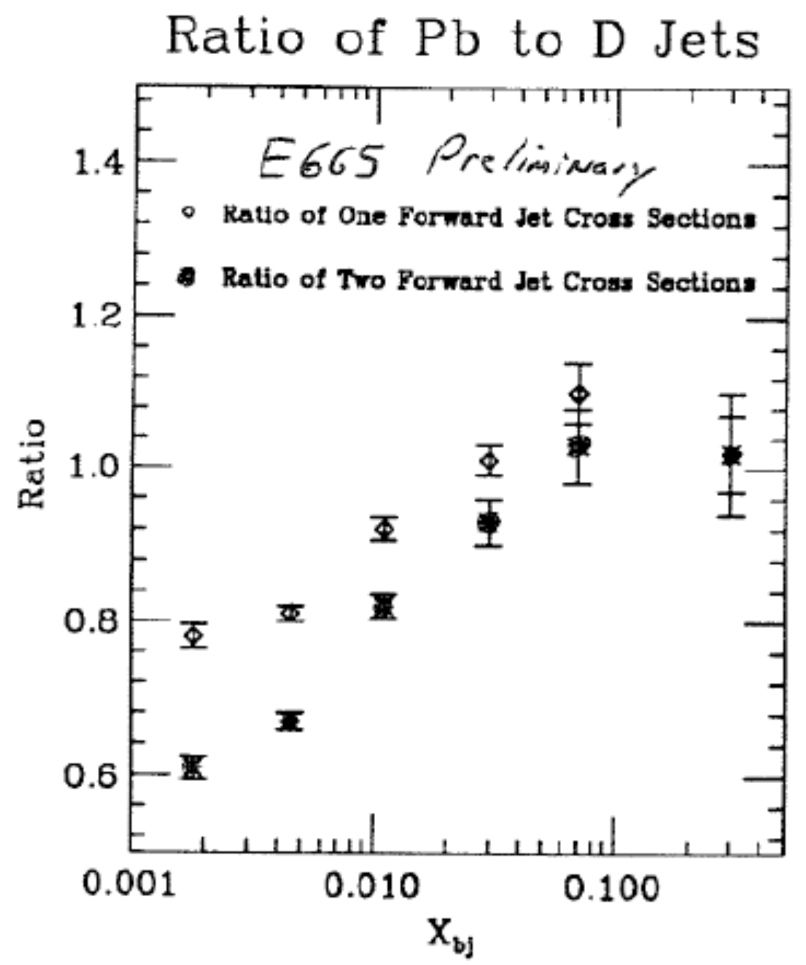

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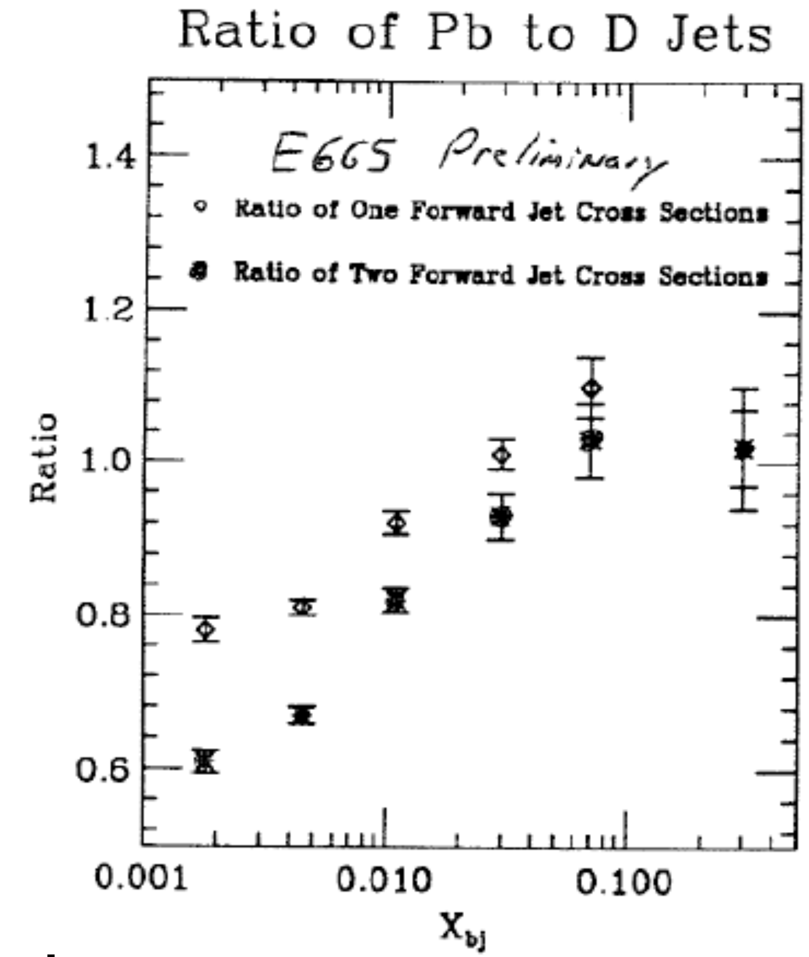
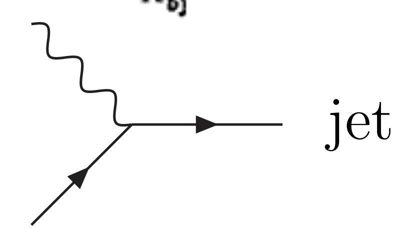


1+1 jets, dominated by q processes → allow study of parton propagation through cold nuclear matter



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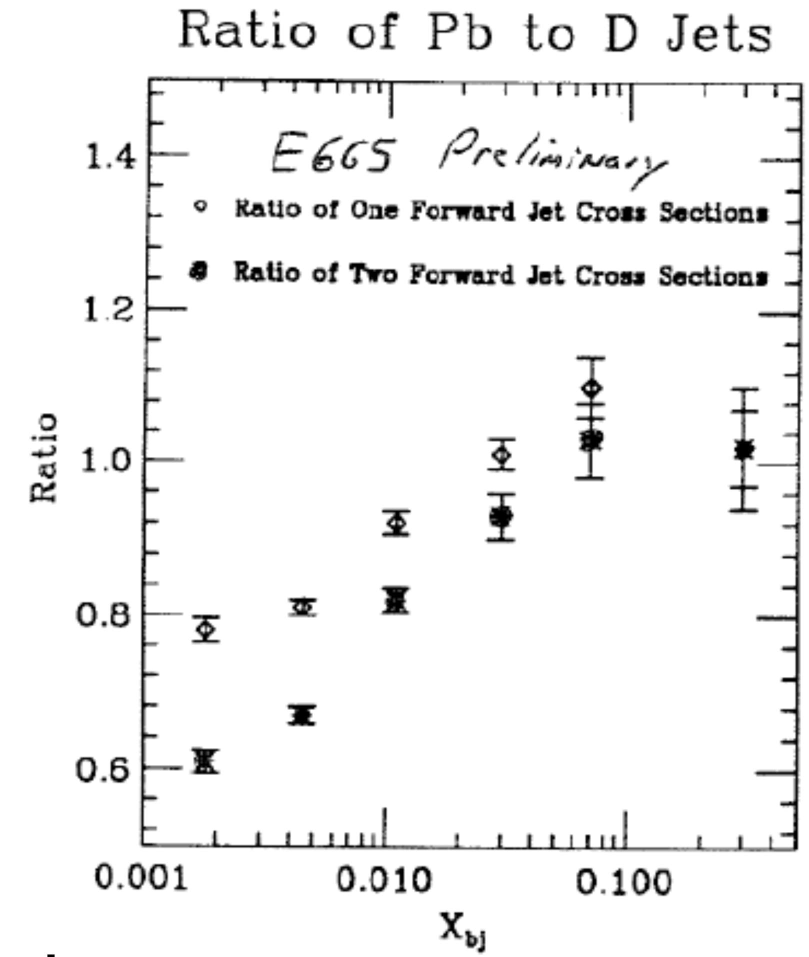

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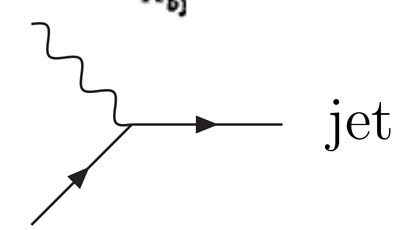

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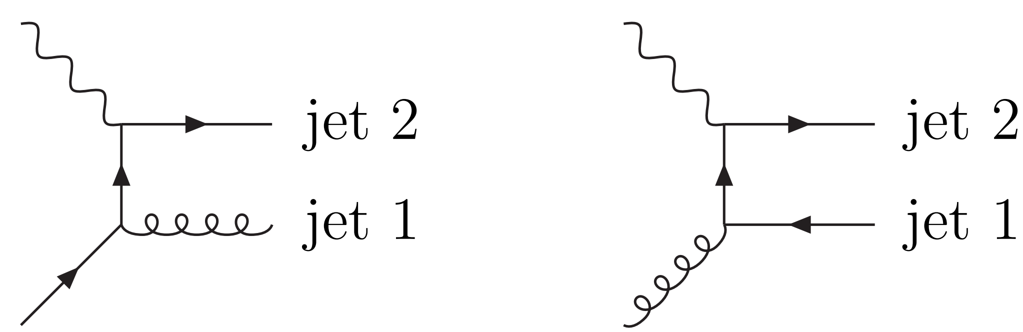

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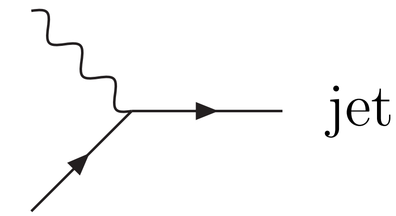

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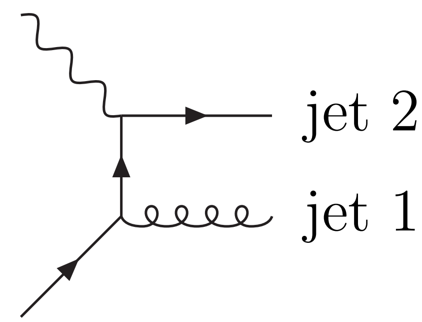

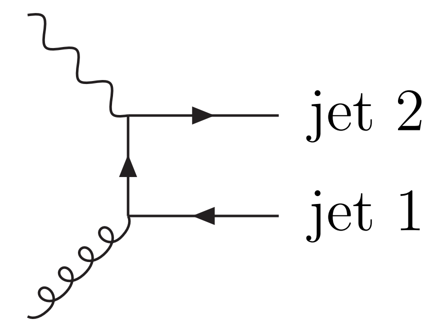

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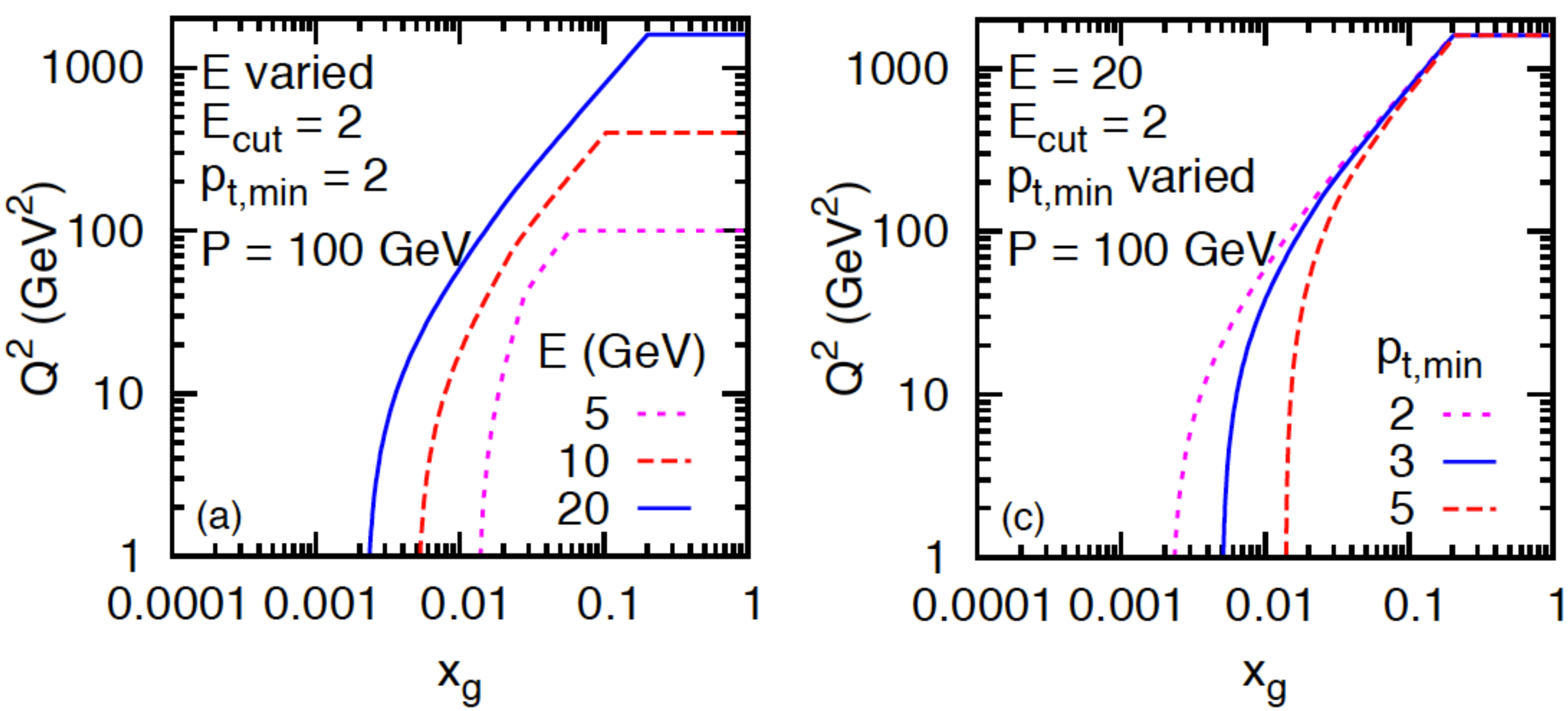
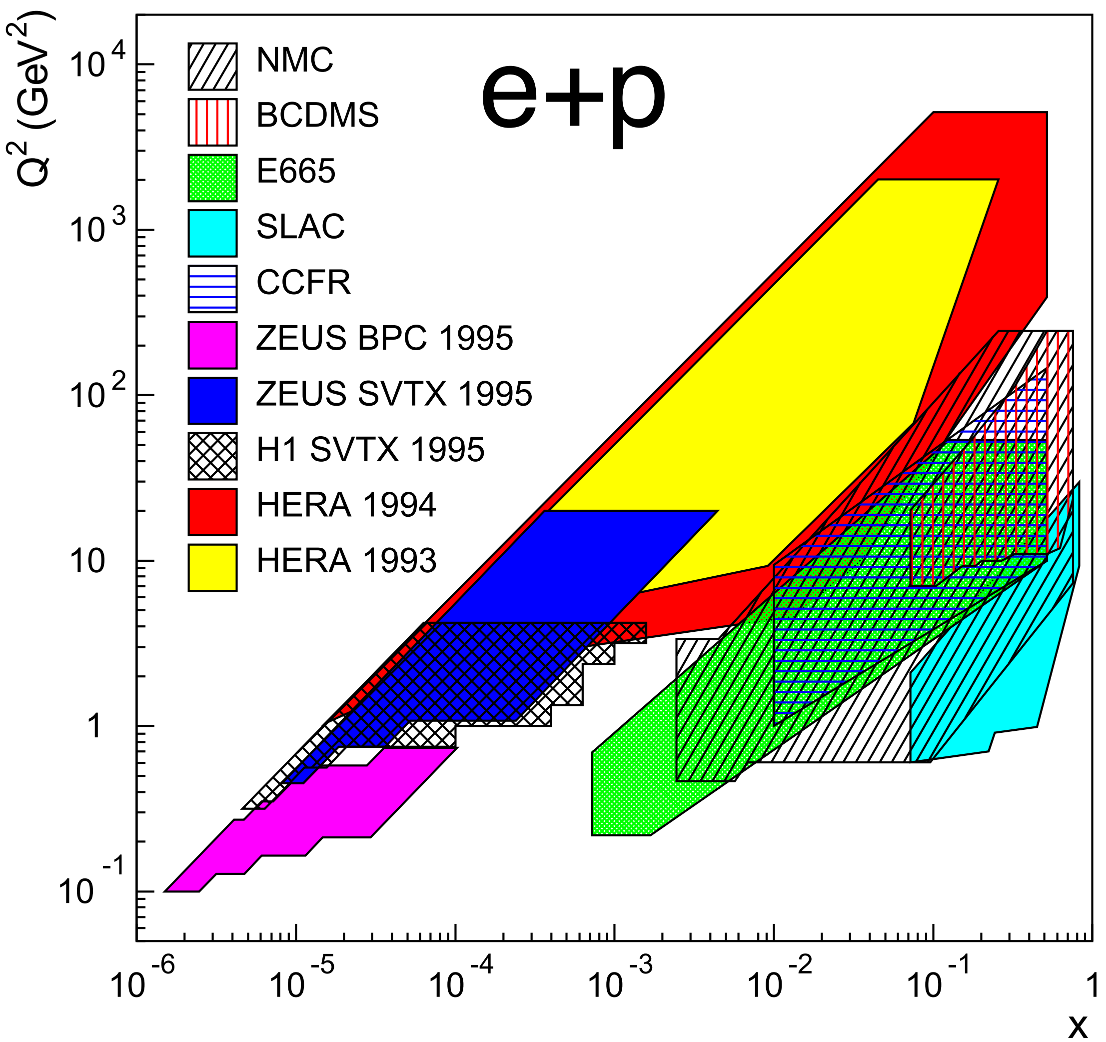
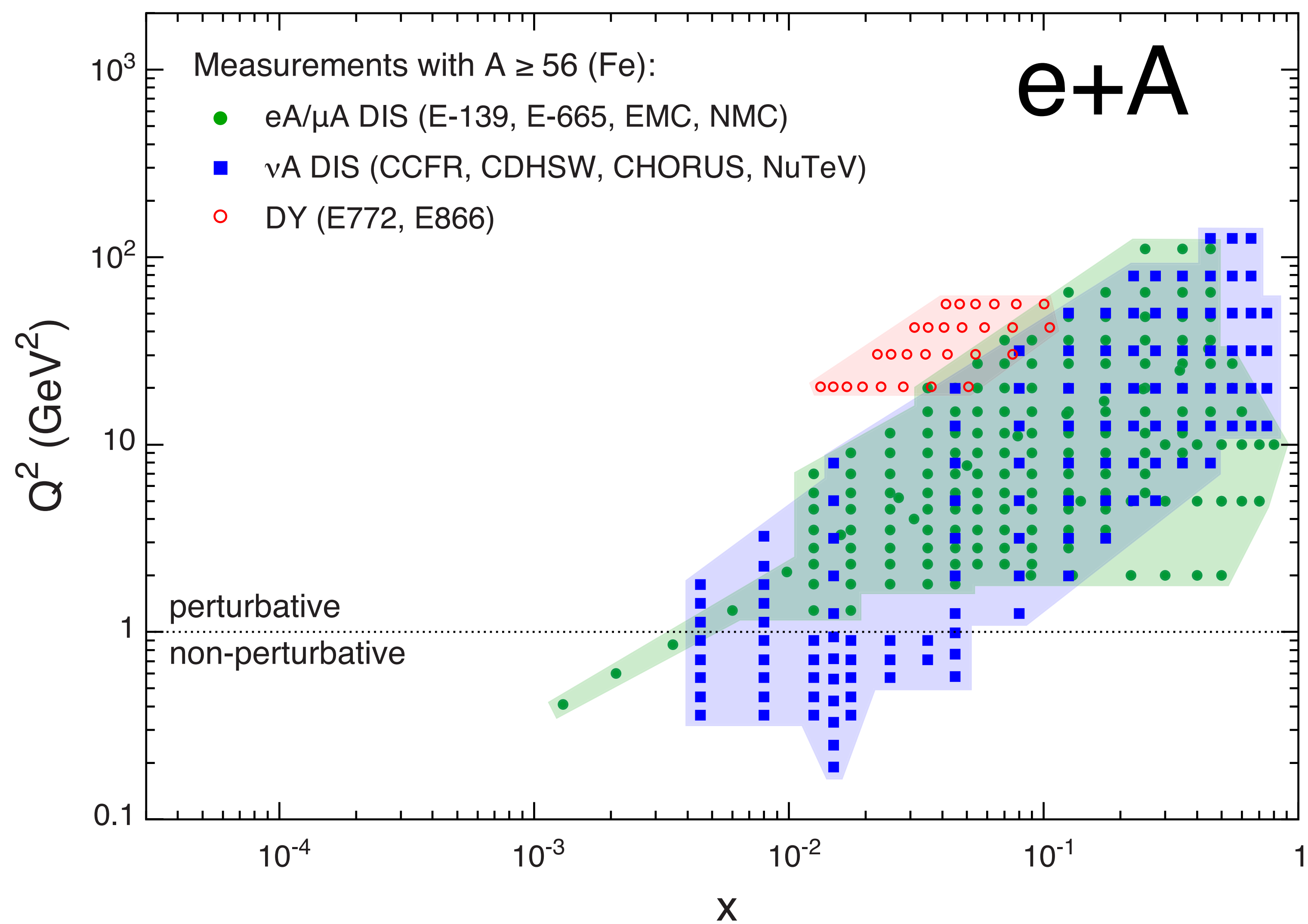


What do we know about the structure of nuclei?





- e+p data covers large part of phase space
  - ➡low x and large Q^2
- e+A data only a small fraction of this (e+A was a fixed target programme at HERA)
  - ➡high-medium x and low Q^2

F_L at an EIC vs F_L at LHeC

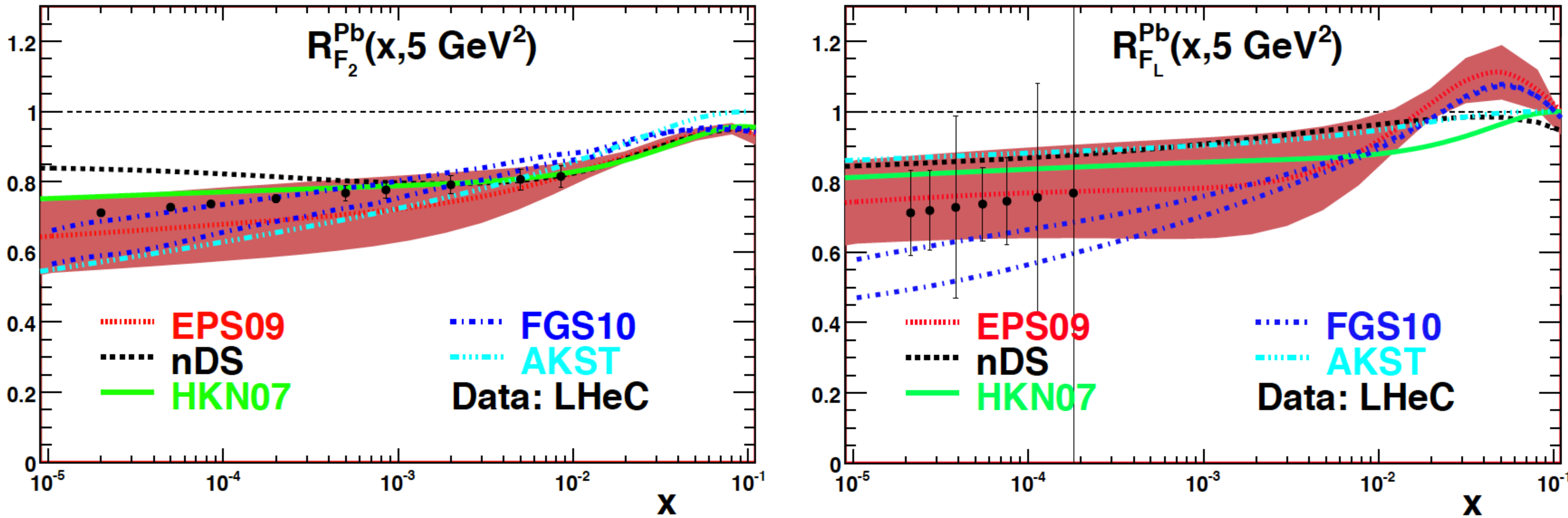
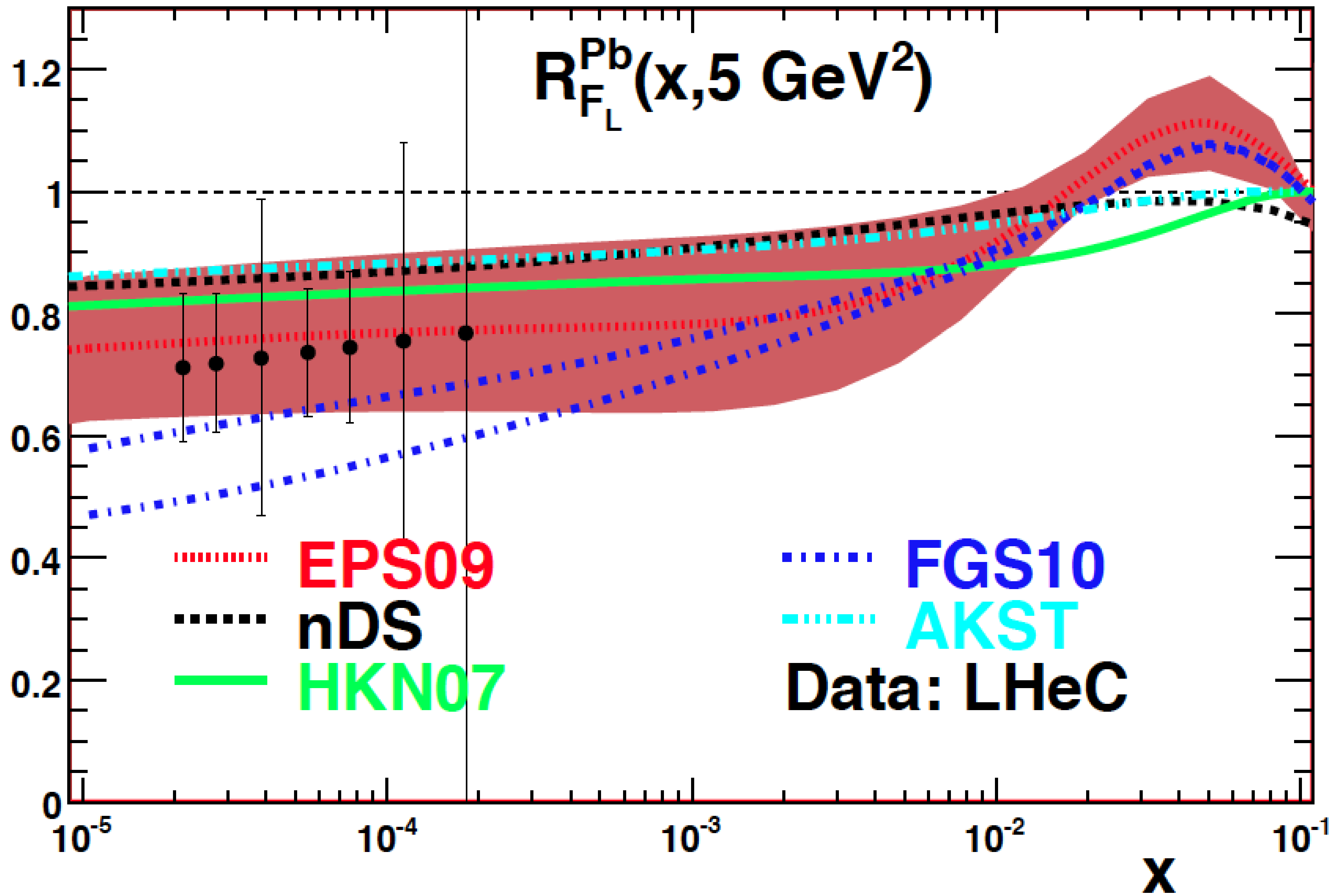


Fig 6.18 of LHEC CDR

- R_{F2} has good coverage with x and small uncertainties
- R_{FL} concentrated at low-x but large uncertainties

F_L at an EIC vs F_L at LHeC



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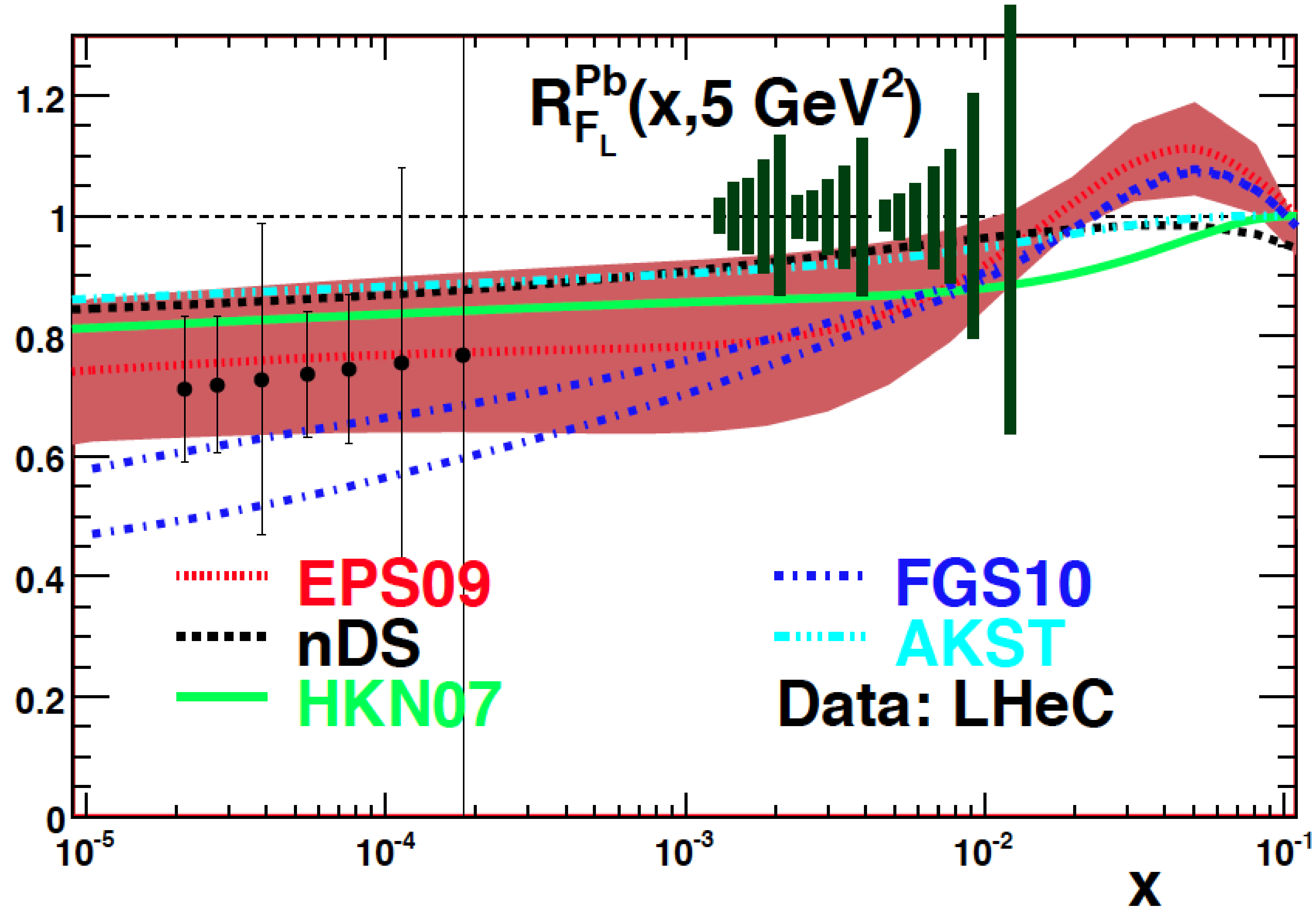
F_L at an EIC vs F_L at LHeC



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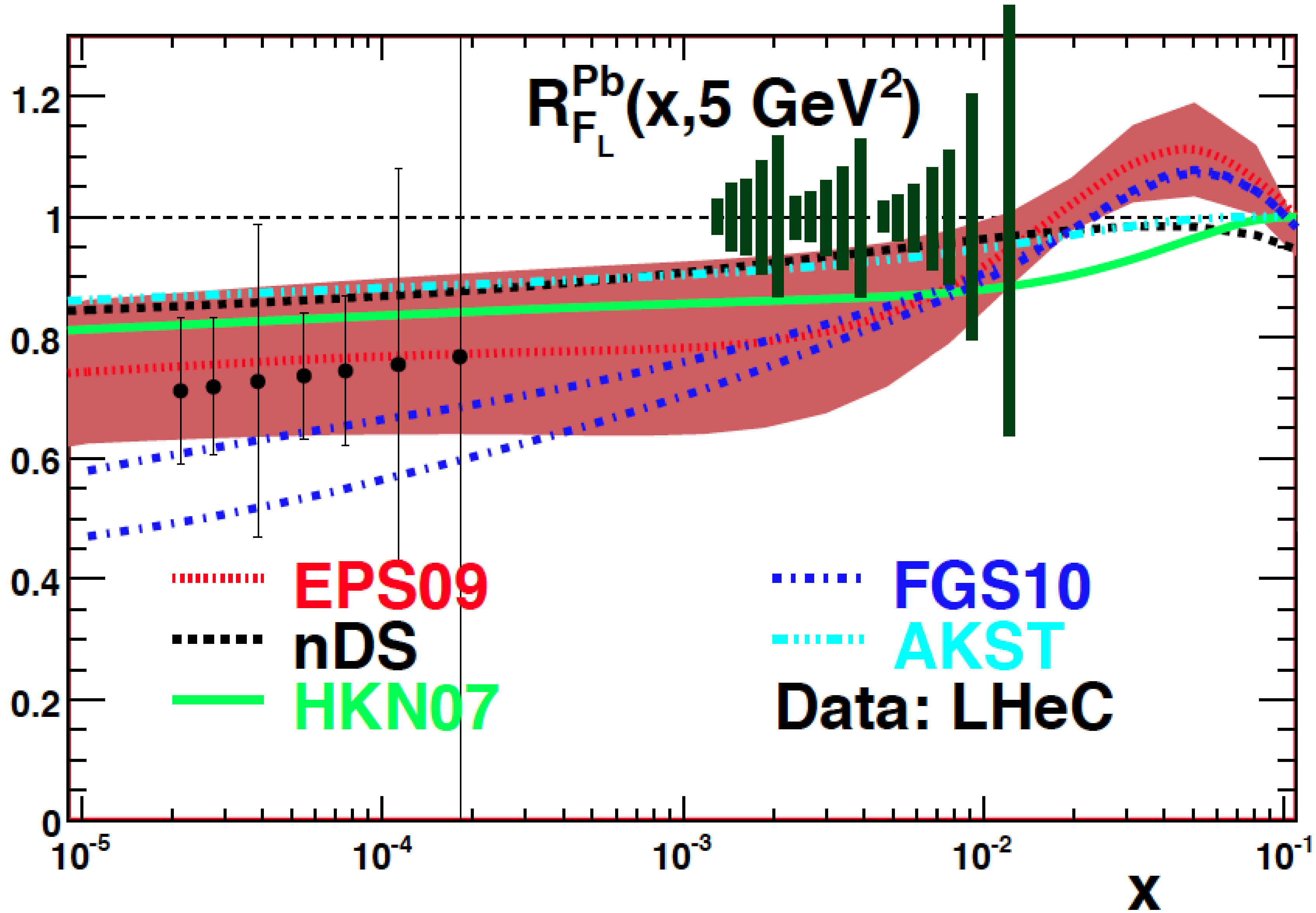
F_L at an EIC vs F_L at LHeC

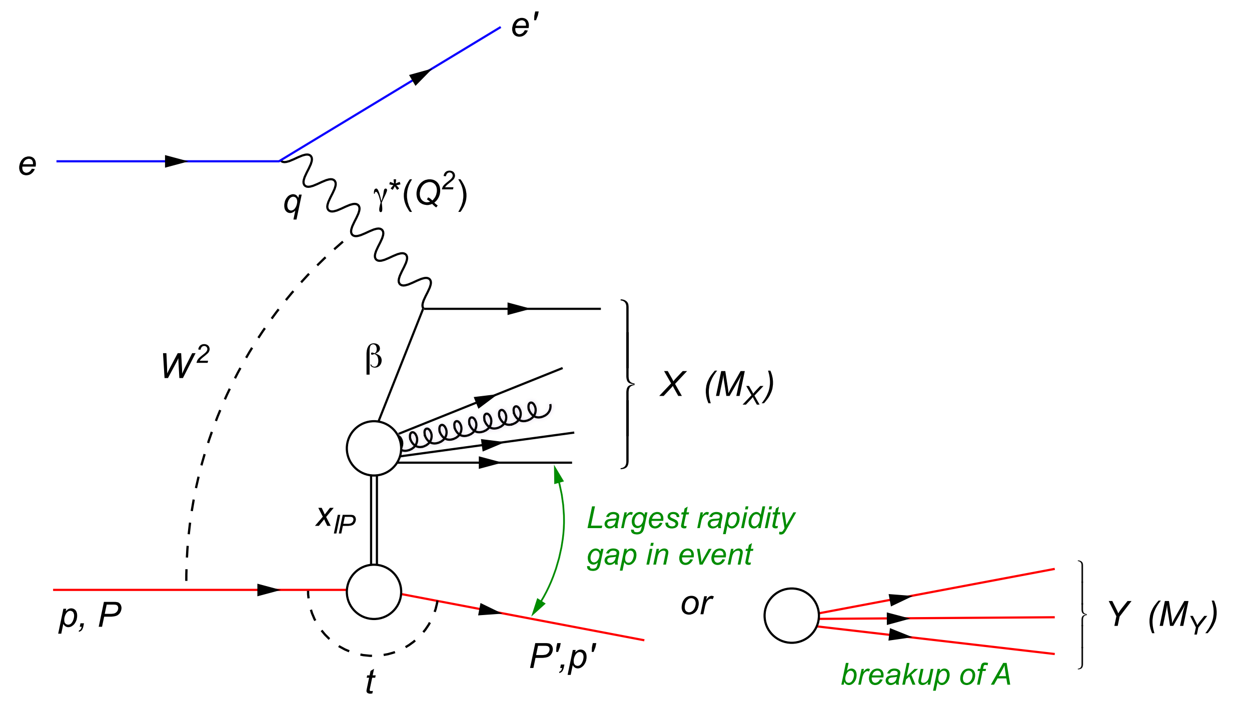


- R_{F2} has good coverage with x and small uncertainties
- R_{FL} concentrated at low-x but large uncertainties

➡EIC data will provide constraints at higher x with smaller error bars

Diffractive Events: Experimental Side

- **How to identify**
- **diffractive events?**



➡ Rapidity Gap

- requires hermetic (large acceptance) detector

➡ Separating coherent from incoherent diffraction

- detector and IR needs to be carefully designed to detect nuclear breakup

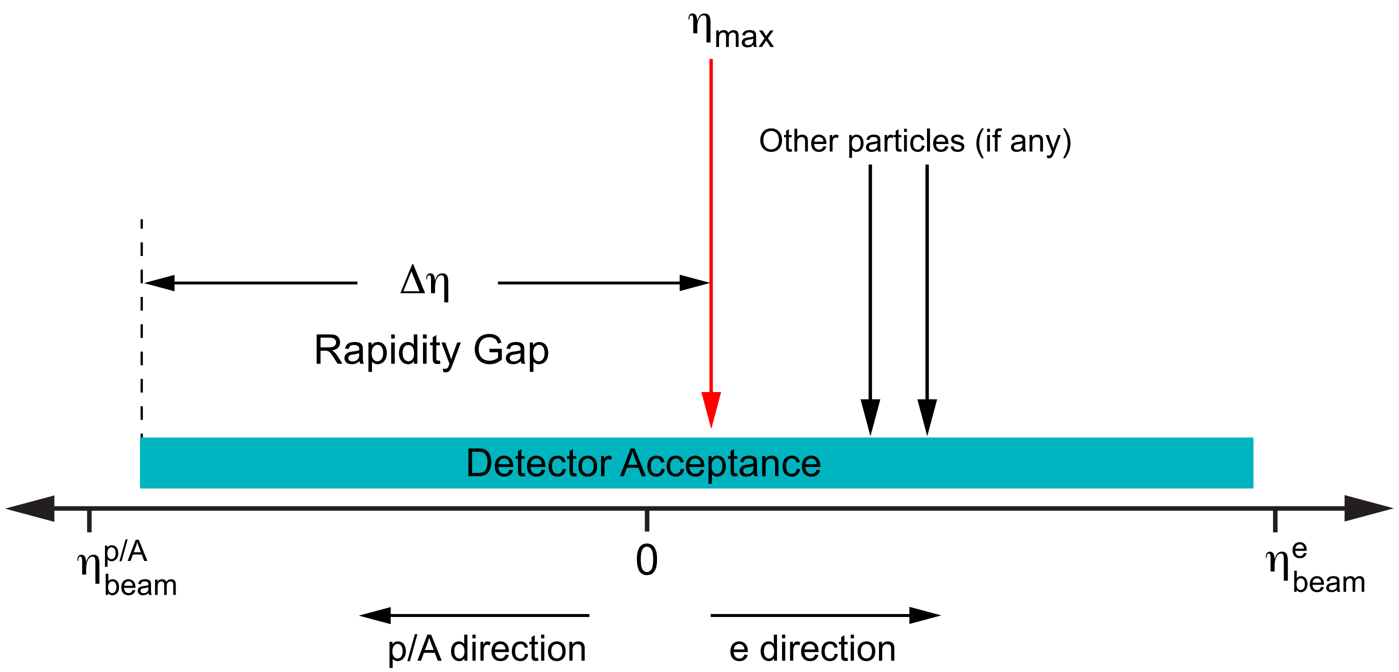
➡ Limitation at a collider

- Coherent: scattered ion cannot be measured, *t* not directly measurable (may be in very light ions)
- Breakup can be detected using emitted *n* and γ, some charged fragments can be measured in Roman Pots

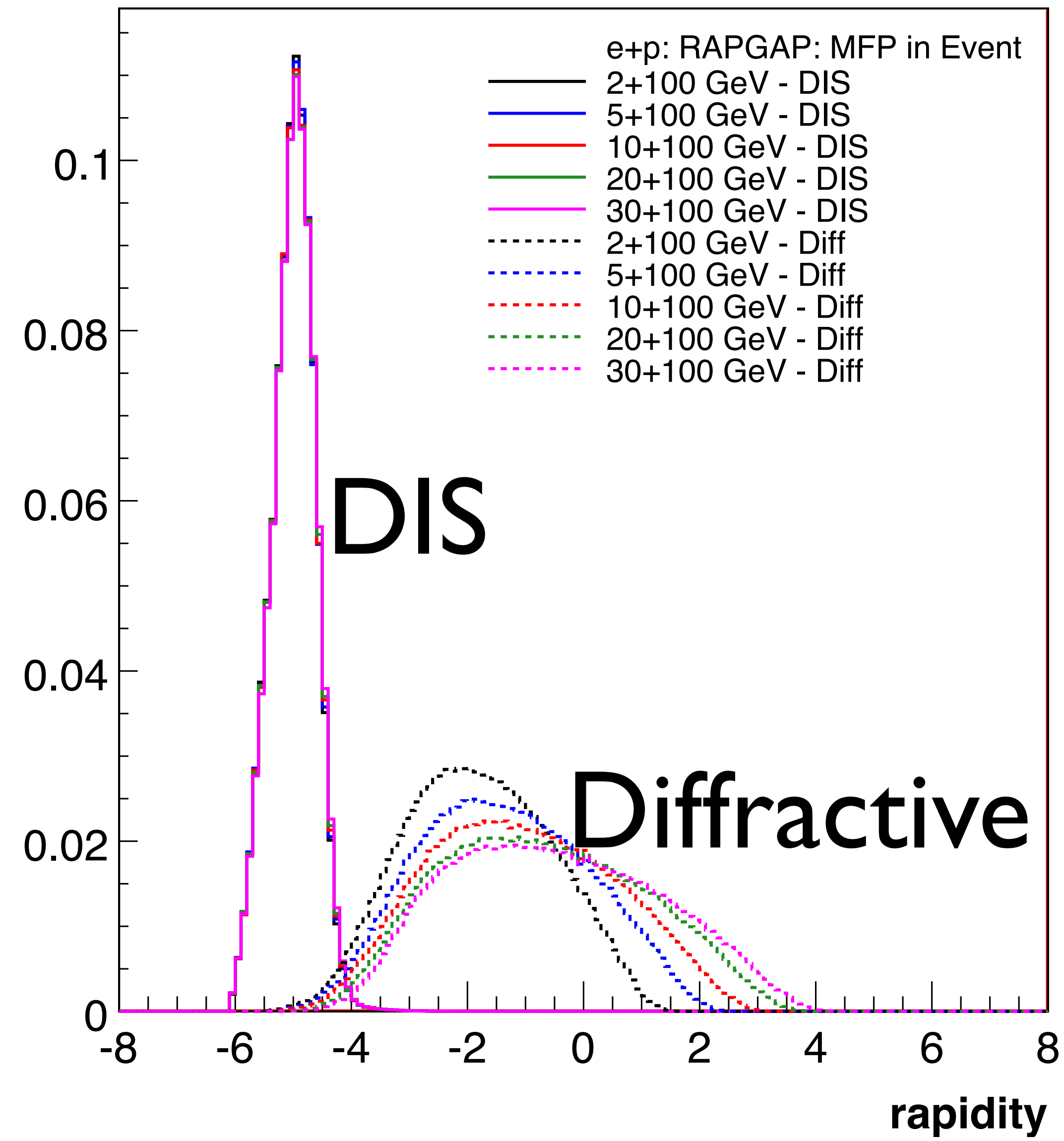
Large Rapidity Gap Method (LRG)

➡ Identify Most Forward Going Particle (MFP)

- Works at HERA but higher √s
- EIC smaller beam rapidities



Diffractive ρ^0 production at EIC: η of MFP



Hermeticity requirement:

- needs just to detector presence
- does not need momentum or PID
- simulations: √s not a show stopper for EIC (can achieve 1% contamination, 80% efficiency)

Detecting Nuclear Breakup

➡ Detecting **all** fragments $p_{A'} = \sum p_n + \sum p_p + \sum p_d + \sum p_\alpha$ ... not possible

➡ Focus on n emission

- Zero-Degree Calorimeter
- Requires careful design of IR

- Additional measurements:
  - Fragments via Roman Pots
  - γ via EMC

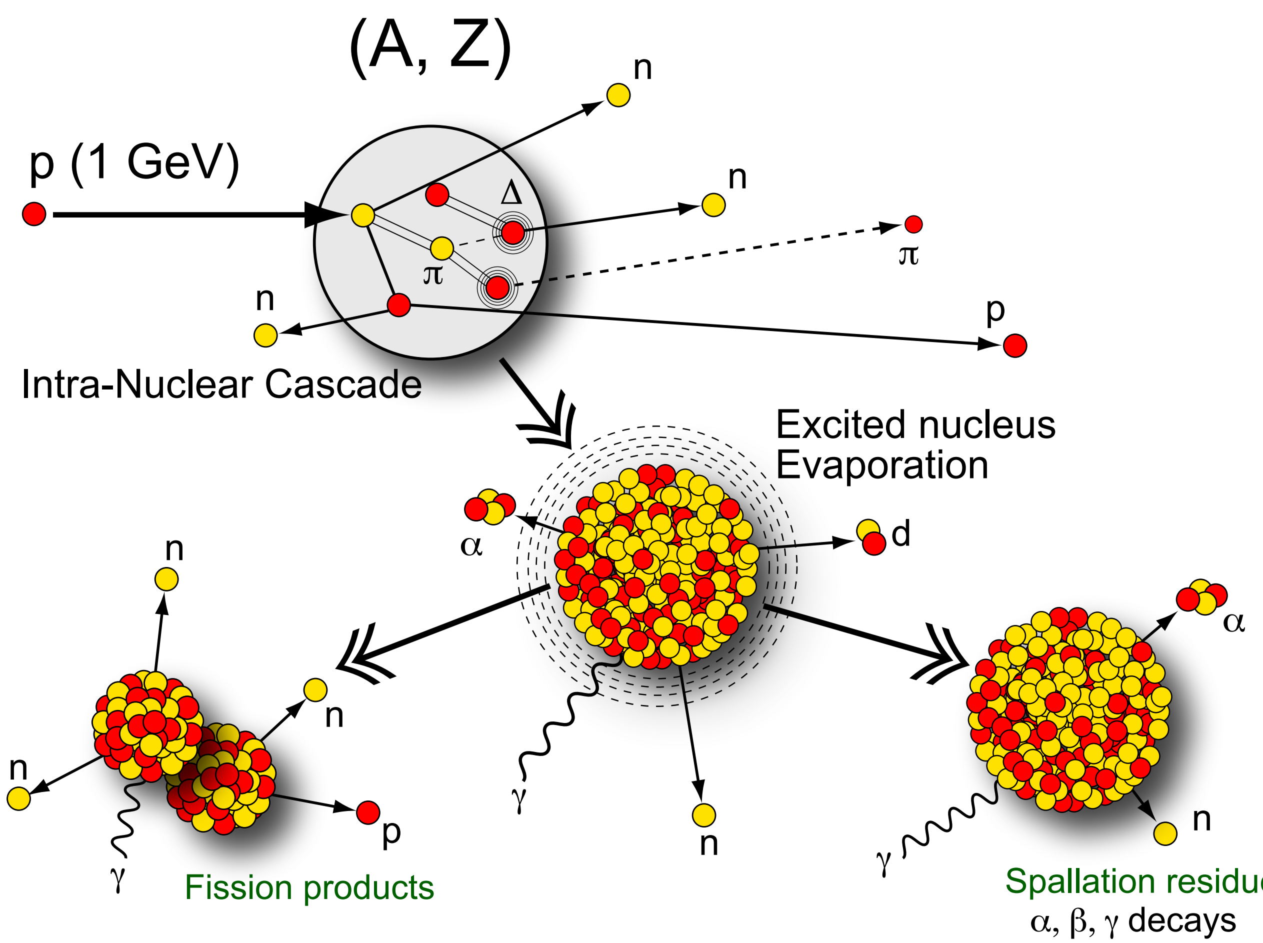
Traditional modelling done in pA:

Intra-Nuclear Cascade

- Particle production
- Remnant Nucleus (A, Z, E*, ...)
- ISABEL, INCL4

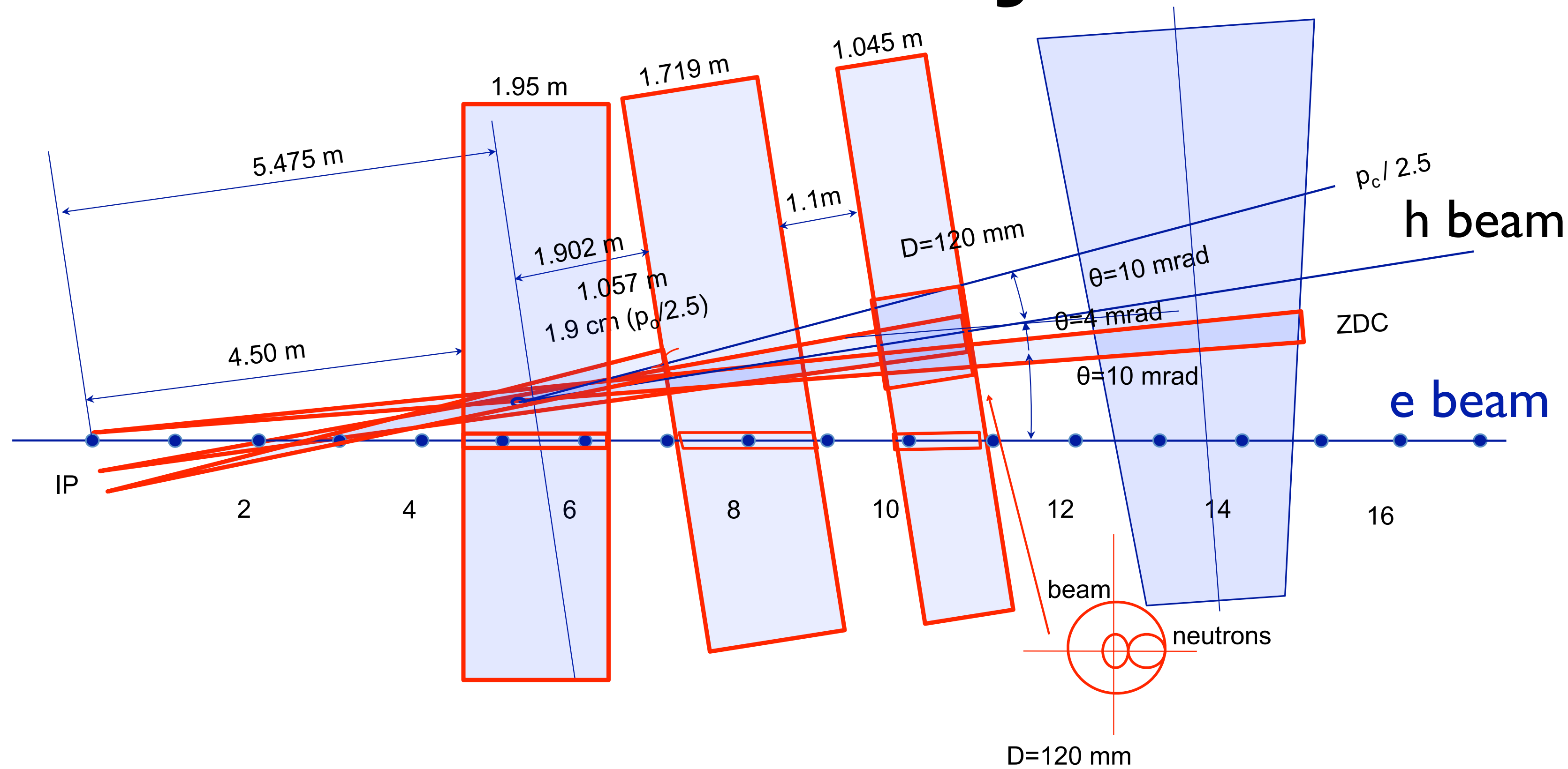
De-Excitation

- Evaporation
- Fission
- Residual Nuclei
- Gemini++, SMM, ABLA (all no γ)



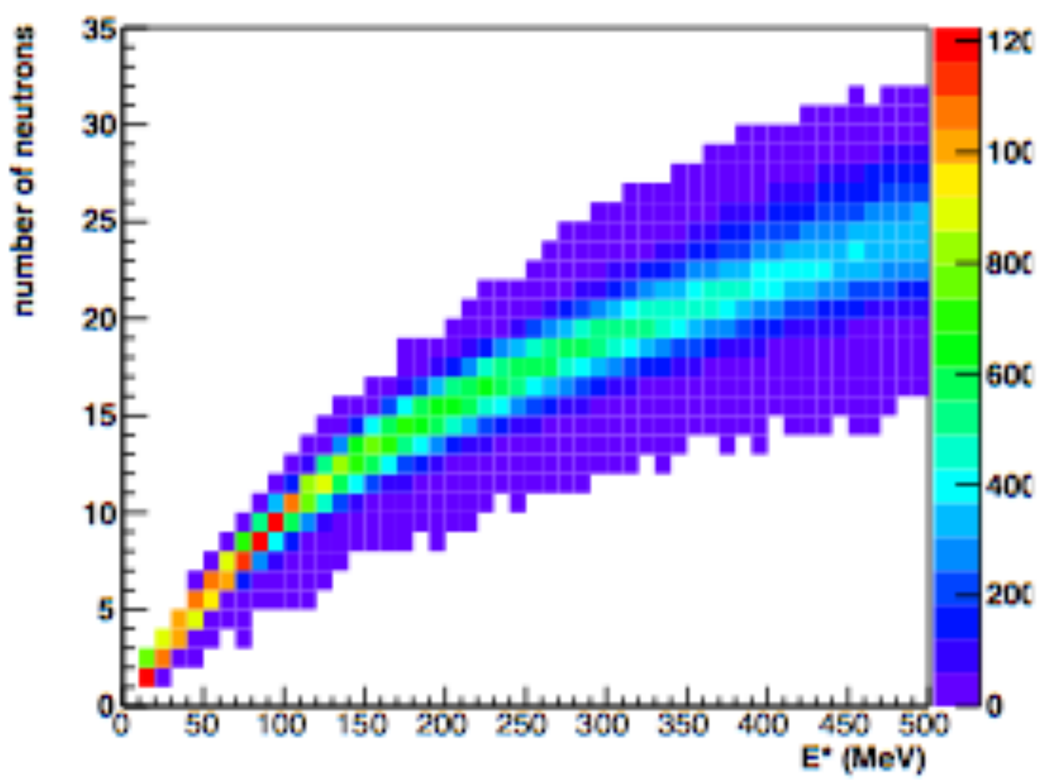
Experimental Reality

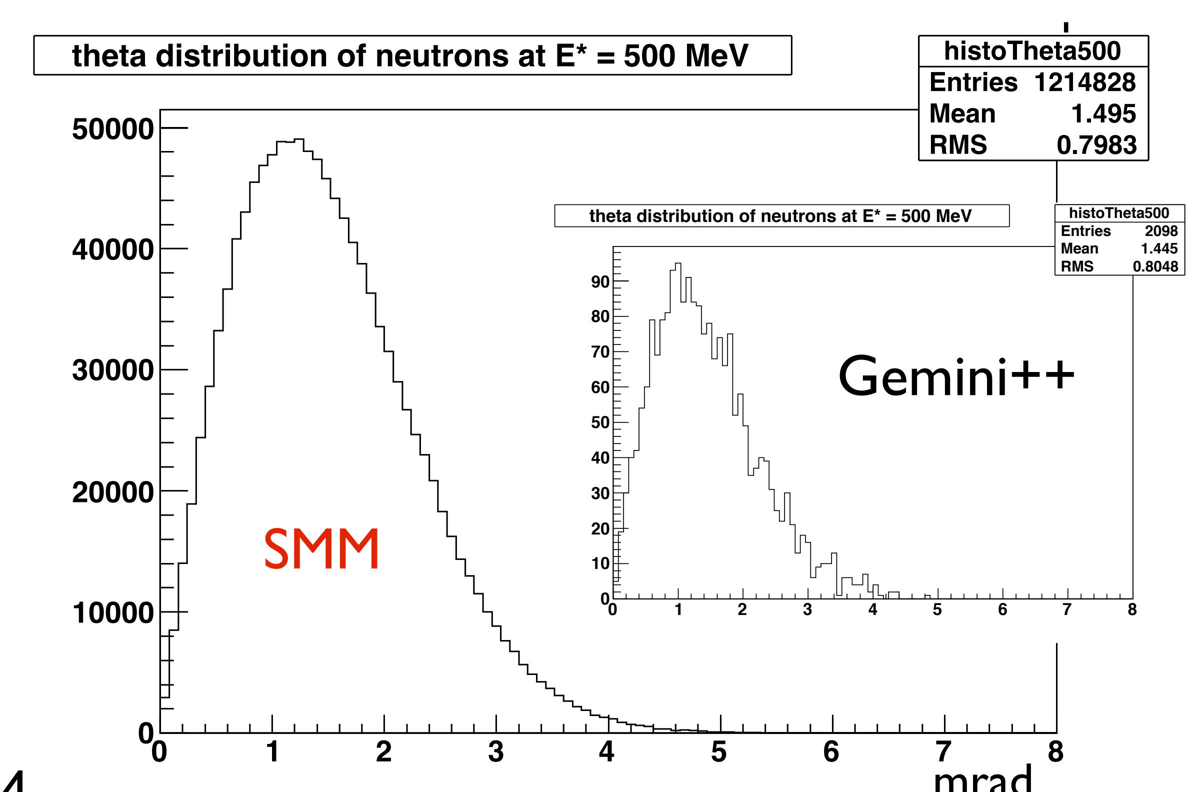
- Here eRHIC IR layout:



- Need ±X mrad opening through triplet for *n* and room for ZDC

- Big questions:
  - ➡ Excitation energy E*?
  - ➡ ep: $d\sigma/M_Y \sim 1/M_Y^2$
  - ➡ eA? Assume ep and use $E^* = M_Y - m_p$ as lower limit





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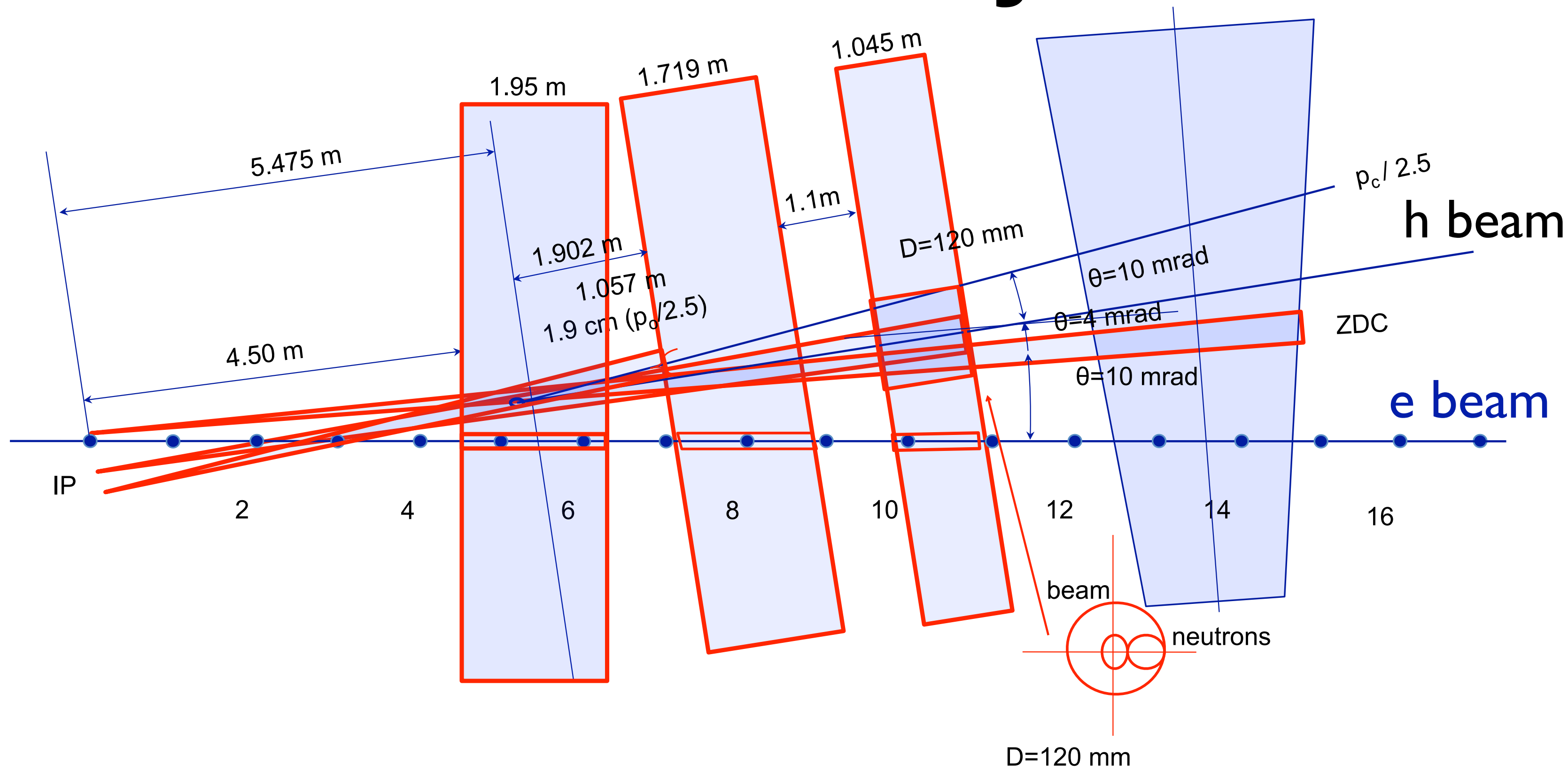

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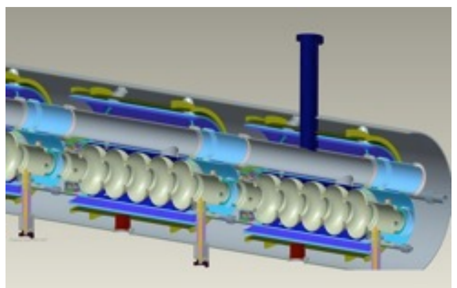
Simulations using Gemini++ & SMM show it works:

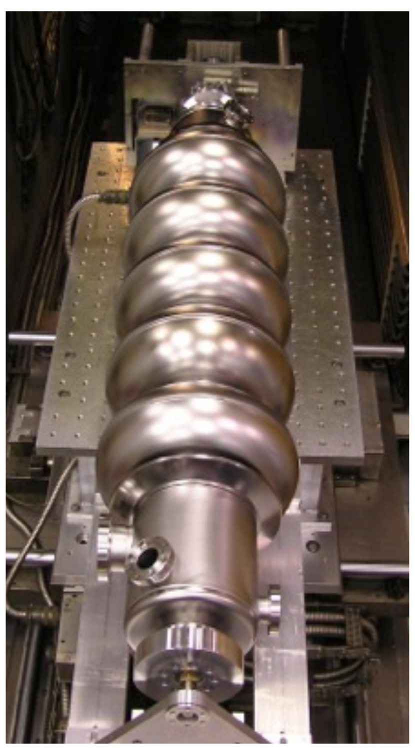
- For $E^*_{tot} \geq 10$ MeV and 2.5 mrad *n* acceptance we have rejection power of at least 10^5.
- Separating incoherent from coherent diffractive events is possible at a collider with *n*-detection via ZDCs alone

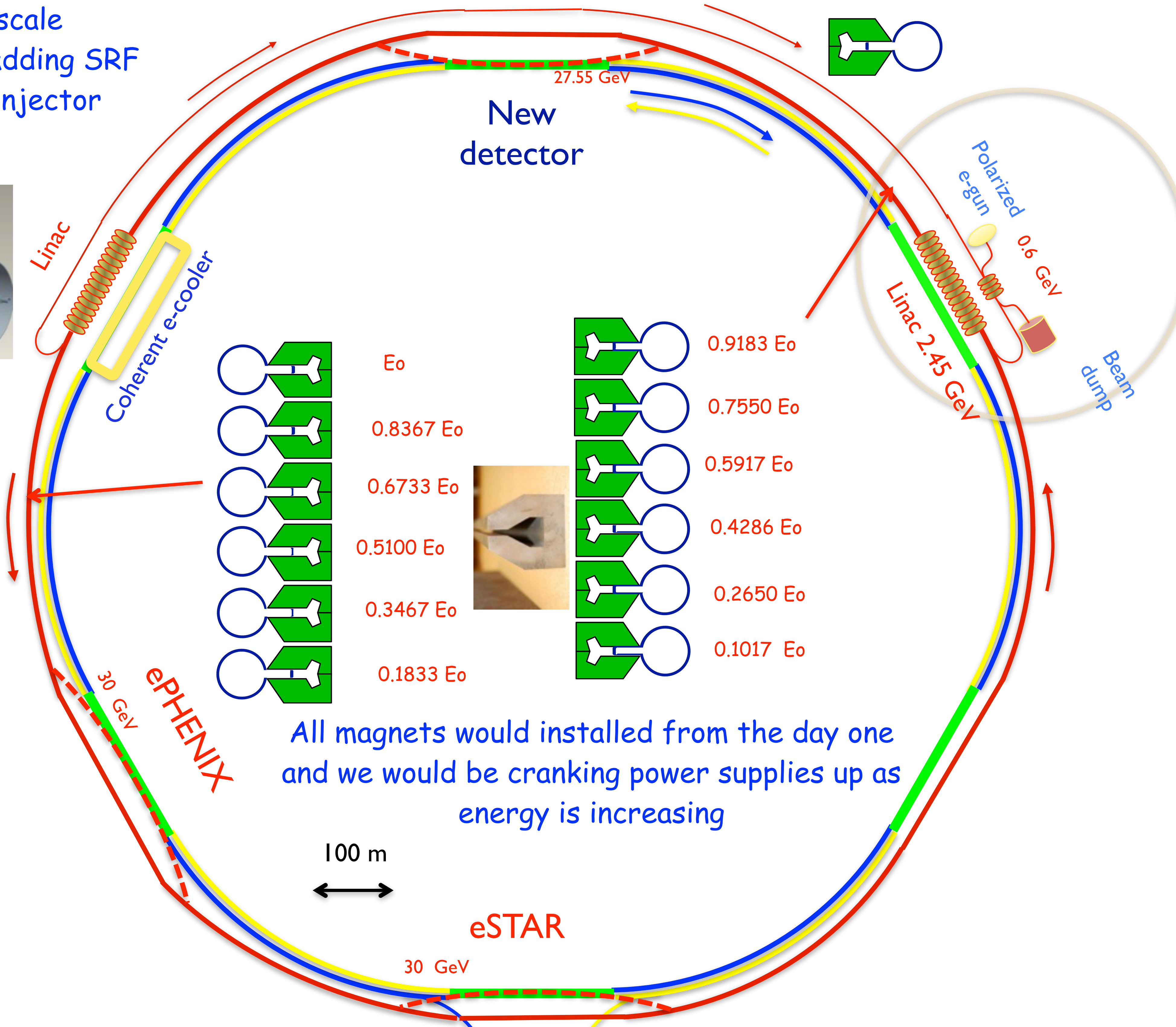
Old Accelerator Design

Staging of eRHIC: E_e: 5 to 30 GeV

All energies scale proportionally by adding SRF cavities to the injector







E/Eo
0.0200
0.1017
0.1833
0.2650
0.3467
0.4283
0.5100
0.5917
0.6733
0.7550
0.8367
0.9183
1.0000